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REVIEW OF LITERATURE RELATED TO ENGINEERING ASPECTS OF GRAIN DUST EXPLOSIONS

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PREPARED BY SCIENCE AND EDUCATION ADMINISTRATION

Abstract

Grain dust, a hazardous material if not properly controlled, can be a fire and explosion hazard as well as a health hazard. This report reviews dust cloud composition and generation, including grain dust generation during grain handling, grain dust evolution from a grain mass into the air, dust entrainment from a dust layer to an airstream, and dust settling from a moving or stagnant cloud. It also reviews dust combustion without explosion, dust explosibility, theoretical analysis of a dust explosion, flammability of mixtures of vapors, gases, and dust clouds, dust cloud detonability, methods of preventing rapid exothermic chemical reactions, and methods of preventing damaging overpressures.

Key words: Dust explosion, grain dust, deflagration, detonation, flammability, dust cloud concentration, minimum explosible concentration, minimum ignition energy, maximum pressure rise, maximum rate of pressure increase, venting, combustion, hybrid explosion.

REVIEW OF LITERATURE RELATED TO ENGINEERING ASPECTS OF GRAIN DUST EXPLOSIONS

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Review of Literature Related to Engineering Aspects of Grain Dust Explosions

David F. Aldis and Fang S. Lai[1]

Introduction

A critical review of published research on grain dust explosions is provided in this publication. Its purpose is to develop an information base for analyzing these explosions and to widen the knowledge concerning grain dust. Areas examined include grain dust hazards and the causes, effects, and prevention of grain dust explosions.

Although the first major grain elevator explosion was reported to the U.S. Department of Agriculture (USDA) in 1898, the Department's dust explosion prevention campaign was in effect as early as 1917. Since then, numerous conferences and symposia have been held to discuss grain dust problems and many reports on studies of dust explosions have been published.

In spite of the early work and significant contribution by a succession of investigators, progress in solving the problem of grain dust explosions has been painfully slow. There are several reasons for lack of progress. First, research effort has been insufficient; and, for the past 60 years, research on the subject has been activated and conducted intermittently. Second, dust explosions are extremely difficult to analyze. Third, the complex environments of elevators and the interacting factors that affect dust explosions make developing a predictable relationship difficult.

Previous dust explosion studies include Shellenberger (1936), who reviewed the literature on sources of ignition, static electricity, direct relation between relative humidity and static electrical charge, and venting. Hughes (1970) reviewed the definition of dust and a dust cloud, dust cloud formation, parameters of dust cloud combustion, dust cloud flammability, and industrial causes and prevention of dust explosions. The most recent book on the subject was written by Bartknecht (1978a).

Palmer (1973) presented an overview of the dust explosion problem in the United Kingdom, Europe, and the United States. He reviewed experimental work on fires in dust layers and explosibility tests that are used in the United Kingdom, Federal German Republic, United States, and other countries. He also reviewed research on theoretical aspects of the ignition of dust and propagation of a dust cloud explosion. Practical methods of avoiding ignition sources in dust atmospheres, venting, dust control, and chemical suppression and its possible use in industrial environments were examined. Palmer's book is the most comprehensive and informative review of dust explosion studies.

In a three-part monograph published by the Chr. Michelsen Institute, Bergen, Norway, Eckhoff (1976a) delved into the basic problems of assessing the ignitability and explosibility of dust clouds using laboratory-scale methods. In addition to reviewing the literature, he discussed his own research results, including an analysis of the minimum ignition energy determined with an electric spark. He found that if the duration of the spark discharge was increased to a point depending on the energy range and the dust, the experimentally determined minimum ignition energy for a given dust cloud decreased markedly. By analyzing

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results from the literature, he predicted that airborne clouds of several materials could be ignited by spark energies of the order of 1 mJ or less, provided the duration of the discharge time was in the order of 0.1 ~ 1.0 m sec. These predictions agreed with his own experimental results.

The second part of Eckhoff's monograph (1976a) concerned experimental analysis of the Hartmann bomb for determining explosion pressures and rates of pressure rise using lycopodium as a test dust. This part of the monograph included publications by Eckhoff (1975) and Eckhoff and Enstad (1976). More recently, an outline of a theoretical analysis by Enstad and Eckhoff was published (Eckhoff 1978c). An analysis of maximum pressures and rates of pressure increase obtained with the Hartmann bomb at the Chr. Michelsen Institute, and values obtained in laboratories in other countries, revealed only moderate discrepancies between mean values and between coefficients of variation. Eckhoff confirmed that the degree of turbulence in the dust cloud during explosions in closed vessels probably had a pronounced effect on the rate of pressure rise, which increased dramatically with increased turbulence.

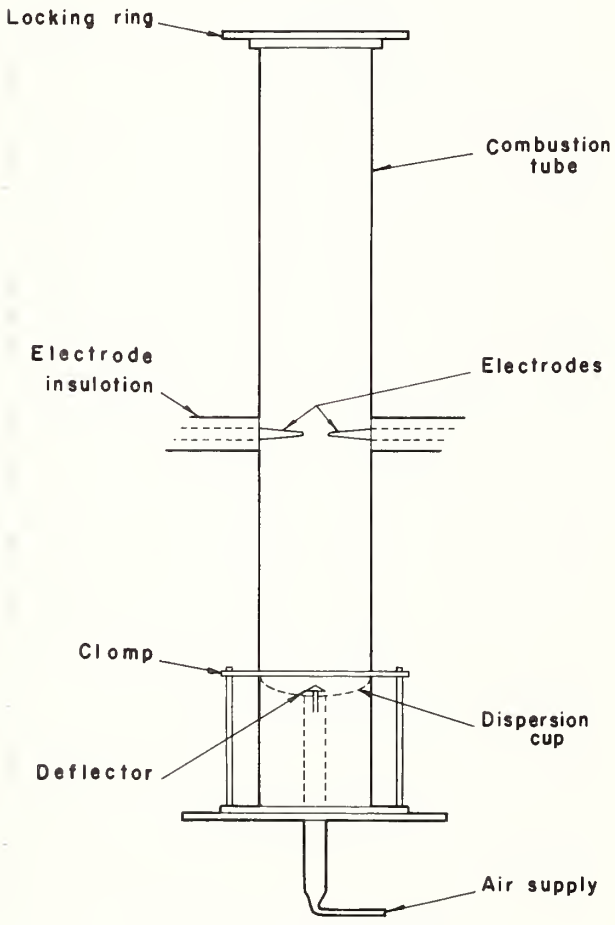

Figure 1.—Hartmann bomb.

In a more recent paper, Eckhoff (1977) discussed the effect of turbulence in small- as well as in large-scale tests. Methods of dust cloud ignition using hot wires, continuous electric sparks, delayed sparks, and effects of spark electrode spacing and initial dust cloud pressure were also investigated. Eckhoff compared the results of testing the same dust for explosibility at different laboratories. Previous attempts at comparing Hartmann bomb data acquired in various laboratories have been few, and efforts to standardize the apparatus and the experimental procedures have been limited. However, the American Society of Testing and Materials recently undertook the task of standardizing the testing procedure for the Hartmann bomb.

In the third part of his monograph, Eckhoff (1976a) described a series of explosibility tests on 12 samples of dust from grain, feedstuffs, and supplementary organic materials (see **Grain Dust**).

Maximum explosive pressure and maximum rate of pressure change for dust clouds are generally measured with the Hartmann bomb. The Bureau of Mines, U. S. Department of the Interior, studied explosibility of various dusts with that apparatus (Jacobson 1961, Dorsett and others 1960). Ishihama and Enomoto (1973) designed another apparatus for measuring maximum rate of pressure rise and maximum pressure of a uniform dust cloud. It consisted of a rotating 10-liter cylinder with an inside wall surface that aids dust dispersion as the cylinder rotates. Uniformity of the dust dispersion is measured by extinction of light passing axially through the cylinder.

Enomoto (1977) used the device to determine maximum pressure and rate of pressure change for corn and potato starch; wheat flour; skim milk powder; and maize, wheat, and milo dust. Maximum explosion pressure versus vola-

tile material content was plotted for various types and particle sizes of dust. The effect of initial pressure on the dimensionless maximum pressure, or ratio of maximum pressure to initial pressure, was linear. A plot of the log of maximum and average rate of pressure change versus a log of dimensionless maximum pressure also was linear. Plots of explosive strength (product of maximum rate of change of pressure and maximum pressure) versus volatile material content for various particle-size fractions of several materials gave smooth nonlinear curves like the relation between explosive strength and average particle size.

Eckhoff's (1976a) previous work on grain dust was summarized (Eckhoff 1977/78). In a recent paper, Eckhoff and Mathisen (1977/78) discussed the effect of dust moisture and the maximum rate of pressure rise, $\left(\frac{dp}{dt}\right)_{max}$. This effect is relevant when attempting to apply small-scale dust-moisture correlations to large-scale situations.

At the Laboratory of Explosives, University of Tokyo, Hikita (1949a) conducted a series of experimental and theoretical studies on dust explosions. He thoroughly reviewed dispersibility and electrification of dust particles. By measuring the dispersibility of many powdered materials by electrified air, he found that the main factor governing the dispersibility of dusts was not the particle-size distribution in the condensed state but the degree of conglomeration of particles in the dispersed state. Electrification of dust particles was a function of particle-size distribution in the dispersed state and the surface characteristics of the dust—the finer the particles, the more positively the dust was electrified. He concluded that the energy of static charges on dust was very small compared with the energy of combustion—about 10 J/gm of dust. Consequently, the static charge had a stabilizing effect on the dispersibility of dust clouds.

Hikita (1949b) examined combustion properties of coal dust in nitrogen, oxygen, and air. When coal dust was heat-treated in a nitrogen atmosphere, it absorbed oxygen before ignition occurred. Thus, heat treatment may provide the proper condition for propagating an explosion. Hikita (1949b) also measured the minimum explosive concentration with various ignition sources. The method of breaking the metal fuse wire by an electric current was the most suitable ignition device. A photographic flash lamp could ignite the dusts of coal, brown charcoal, and aluminum. The minimum explosive concentrations of most dust samples were in the range of 400 to 600 gm/m^3. Flame-suppressing effects of inorganic salts, such as alkali halides, for a coal dust explosion were examined using as the ignition source an electrical spark emitted between iron poles coated with a thin salt layer. Experimental results showed the remarkable ability of I_2, KI, NaCl, KCl, KBr, $NaNO_3$, and KNO_3 to suppress the ignition of coal dust.

Hikita (1949c) measured the rate of flame propagation in dust clouds by a rotating camera. The discontinuity and fluctuation in the flame front, the movement of burning particles, and the time of combustion were measured using the photographs. Generally, the initial speed of flame propagation was slow (about 10 m/sec) and the optimum dust concentration was in the range of 200 to 500 gm/m^3. Under favorable dispersion conditions, the flame speed increased to about 100 m/sec. Schlieren photographs of dust explosions and structure of hot gas fronts were examined. However, Hikita (1949c) failed to establish the detonation state of a dust explosion.

Finally, Hikita (1949d) conducted a series of theoretical studies on dust explosions. The ideal detonation characteristics of a coal dust were computed by hydrodynamic detonation theory. Calculated detonation velocity and temperature were maximum at the dust concentration stoichiometric ratio and decreased proportionally to the logarithm of concentration with increasing or decreasing dust concentrations. It was assumed that the diffusion resistance of oxygen into an intact carbon surface was the rate controlling factor. Eyring's theory of stability of detonation was applied, and the possibility of a stable detonation of coal dust was determined. Hikita (1949d) concluded that an ideal detonation would not occur, but a deflagration having a flame velocity less than 1,000 m/sec was possible. He introduced theoretical analyses

involving the ignition energies, upper and lower limits of dust concentration, and particle size.

In October 1977, the International Symposium on Grain Dust Explosions was held in Kansas City. The papers covered a wide range of experimental, theoretical, and applied research topics. Experimental studies were presented on the measurement of explosion pressure and the rate of pressure change. Correlations of the volatile matter content of dust, dust concentration, and particle-size distribution versus the location in a grain elevator, static electricity control, and experimental effects of grain dust moisture content were noted. Theoretical analyses were presented for estimating ignition temperature, flame propagation, flame propagation speed, minimum explosive concentration, effectiveness of cloud ionization for dust control and of water mists for explosion propagation control. Applied research topics included headhouse and texas houses made of sheet metal without concrete encasement, redesigned bearing locations, bearing temperature sensors, bucket conveyor motion sensors, and computer systems for instrumentation monitoring, operator warning, and controlled machine shutdown.

Another symposium on grain dust control, handling, and use sponsored by the American Association of Cereal Chemists (AACC), was held in San Francisco in 1977. Papers published in *Cereal Foods World* by AACC covered pyrolysis of grain dust, electrostatic initiation of an explosion in dust, dust control in loading, necessary vent areas, and causes and prevention of grain dust explosions (Chiotti and Morris 1978, Maness 1978, Pacquer 1978, Cocke and others 1978, Pratt 1978, Eckhoff 1978b, Moodie 1978).

In 1978, the Industrial Gas Cleaning Institute sponsored a symposium on Explosion Protection for Dust Control Apparatus. A cross-section panel discussed economics, personnel and legal impacts, and actual experiences.

The most recent symposium on dust explosions, in Washington, D.C., in 1978, was the International Symposium on Grain Elevator Explosions sponsored by the National Academy of Sciences on behalf of USDA. The collection of preprinted papers included both general reviews and specific studies of selected dust explosion problems. Some of the topics included control of electrostatic ignition of dust clouds, analysis of instrumentation for identifying potentially explosive environments, and grain elevator inspection and operation guidelines, as seen by insurance companies. Other topics included proximate analysis and explosibility of industrial grain dusts, dust control by a charged-water vapor fog, a review of research conducted at Ciba-Geigy (Switzerland) on dust and vapor explosions, a review of detonability of dust clouds, and a review of the perspective of the grain dust explosion problem held by the National Institute for Occupational Safety and Health.

Research on dust fires and explosions was reviewed and analyzed by Napier (1977). He reviewed data on ignition temperatures of single magnesium particles. The temperature ranged from 790° to 655°C for particles ranging from 15 μm to 55 μm in diameter. Ignition temperatures of wheat flour layers were reported to be between 300° and 285°C for layers 3-mm and 10-mm thick. The linear burning velocities in dust trains were reported to be 2×10^{-3} cm(sec)$^{-1}$ for coal dust and 4×10^{-3} cm(sec)$^{-1}$ for starch. Some of the other data reviewed included the minimum explosible concentration of corn starch, 45 g m^{-3}, minimum ignition energy of corn starch, 60 mJ, and the effect of aluminum particle size on the minimum explosive concentration, minimum ignition energy, and rate of pressure rise. Napier (1977) reported that the minimum explosible concentration was 45 g m^{-3} for 10 μm diameter aluminum particles and 100 g m^{-3} 100 μm diameter particles, the minimum ignition energy was 30 mJ for 10 μm diameter particles and 200 mJ for 100 μm diameter particles, and the maximum rate of pressure rise was 1.72×10^5 pa/sec for 100 μm diameter aluminum particles and 2.06×10^4 pa/sec for 10μm diameter particles. The burning velocity for coal dust burned in air ranged from 12 cm/sec to 4 cm/sec for coal particles with diameters of 11 μm to 45 μm.

Griffith's review (1978) of dust explosions concerned flame propagation and detonability. Griffith explored whether the size of the explosion vessel necessary to establish a dust cloud detonation was so large that the contribution of wall effects might make a steady detonation of a dust cloud difficult to achieve.

Grain Dust

Definition

Particulate matter can be divided into three main classes, namely, dust, smoke, and haze, although the demarcation line is not always clear (Friedlander 1977). Dust consists of various sized solid particles formed by disintegration processes. Smoke is a suspension of fine liquid or solid particles produced by burning and condensation. Haze consists of droplets formed by condensation or liquid atomization. Grain dust is solid particles that become airborne during grain handling. In practice, grain dust includes all material collected by a dust control system. The capture velocity of dust of the dust control system is well below the terminal velocity of grain that prevents the capture of grain (Committee on Industrial Ventilation 1972).

Properties

Properties and behavior of grain dust are greatly affected by size, shape, density, surface area, chemical composition, and microbiological characteristics of the dust. These characteristics are directly related to dust cloud formation. Understanding the relation among them is a prerequisite to analyzing grain dust explosions.

Particle-size distribution and dust concentration in ducts of turbulently flowing air were presented by Zenker (1972). Velocity profiles of dust-air mixtures were strongly affected by particle size of the dust and its size distribution. Specific mass-flow density versus radial position is a function of dust concentration.

Eckhoff (1976a), as part of an experimental investigation of 12 samples of grain dusts, feedstuffs, and other natural organic materials, found a correlation between the rate of pressure rise from a dust cloud explosion in a Hartmann bomb and the starch plus fiber content, surface area per unit volume of dust, and moisture content of the dust. Differences in surface area and chemical composition of dust from several types of grains and other food products were observed. Electron micrographs and particle-size distributions were presented for several dust samples. Statistical analyses of the maximum pressure (P_{max}) and the maximum rate of pressure rise $\left(\frac{dP}{dt}\right)_{max}$ data from replicate Hartmann bomb tests with the 12 dust samples indicated that the data had a normal distribution. For P_{max}, the coefficients of variation for most dusts were between 0.05 and 0.10; for $\left(\frac{dP}{dt}\right)_{max}$, they ranged from 0.20 to 0.40. An attempt to correlate P_{max} and $\left(\frac{dP}{dt}\right)_{max}$ with the heat of combustion for dry dusts was unsuccessful. Two dusts with the highest heat of combustion were the least explosible. A positive correlation, however, was found between $\left(\frac{dP}{dt}\right)_{max}$ and content of starch and fiber. For starches and fish powder, Eckhoff (1976a) found

$$\left(\frac{dP}{dt}\right)_{max} = K\ S \qquad [1]$$

where

$\left(\frac{dP}{dt}\right)_{max}$ = maximum rate of pressure rise, bar/sec

K = a constant that depends on the chemical composition; the constant is 1250 for starch and 450 for fish powder mainly protein, bar·gm/sec·m²

S = specific surface area, m²/gm

For the group of dusts under investigation, the assumption was made that the K value for starch also applied to cellulose fiber, and the value found for fish powder applied to various fractions including protein and organic compounds other than starch, fiber, and ash. Equation [1] was rewritten as

$$\left(\frac{dP}{dt}\right)_{max} = \left[800 \cdot \frac{R}{100} + 450\right] \cdot S \qquad [2]$$

where

R = percent of starch and fiber

Eckhoff's (1976a) book is an excellent account of his outstanding research program on the experimental analysis of grain dust explosions.

Enomoto (1977) plotted the volatile material contents of several kinds of dust against the explosion strength of explosive dust clouds. The

explosion strength was 6[(kg cm^{-2})(kg cm^{-2} sec^{-1})] for first Maja coal and 400 [(kg cm^{-2})(kg cm^{-2} sec^{-1})] for corn starch; the volatile material contents of the dusts were 30 percent and 99 percent, respectively.

Farant and Moore (1978) examined health problems associated with grain dust. Data were presented from 8 terminal, 9 intermediate, and 14 country grain elevators. Airborne dust was sampled with open faced monitors, 10-mm nylon cyclone respirable mass samplers, and an Anderson mini-sampler. The collected dust was analyzed for particle-size distribution with a Coulter counter using a 100 μm diameter aperture. Air samples were taken with portable pumps attached to elevator employees and at fixed locations in the elevator. The samples were analyzed for particle-size distribution, quartz content, inorganic material content, fungal spores, and total respirable dust concentration. The spores in barley and wheat dust samples were from *Ustilago*, *Aspergillus*, and *Mucor* species of mold. The highest dust concentration was in a transfer elevator gallery. One personal sampler collected an average of 1.00 gm of dust per m^3 of air in 1 hour.

A detailed study of the chemical and physical composition of grain dust was presented by Martin (1978). Fat, fiber, ash, protein, starch, and trace element contents in dust from corn, sorghum, soybean, and wheat were determined for each type dust, each from three elevators. Data on the particle-size distribution of the grain dust samples using four instruments (HIAC, Whitby sedimentation, Coulter counter, and Microtrak)[2] were presented. Evidence of a shift in the particle-size distribution because of the particle-collection method was found. Micrographs of the dust showed that the assumption of a spherical dust particle was acceptable for corn dust but not for wheat dust. Capture velocities of bees wings from corn dust were 0.533 m/sec for a 1.74-mm^2 surface area particle and 0.975 m/sec for a 2.06-mm^2 surface area particle. Comparison of Martin's and Eckhoff's data (Eckhoff 1976a) indicated that the measurements of chemical and physical composition of grain dust were in the same order of magnitude.

Giltaire and Dangreaux (1978) analyzed the characteristics and explosibility of several kinds of dust including wood sawdust and wheat flour. In addition to particle-size distribution, surface area, heat of combustion, minimum ignition energy, and maximum pressure and rate of pressure rise in the Hartmann bomb, they reported the mass fraction of weight of carbon and hydrogen in each of the dust samples and differential thermal analyses data. Percentage of carbon, by weight, in wheat flour was 45.9 percent, and the percentage of hydrogen was 6.6 percent. If one assumed that wheat flour contained only hydrogen, carbon, oxygen, and nitrogen and that the nitrogen content was 2 percent, the percent oxygen in wheat flour would be 45 percent by weight. Differential thermal analysis indicated that wheat flour undergoes an exothermic reaction at 160°, 400°, and 620°C.

Analysis of grain dust reveals that it is chemically similar to the grain from which it is generated. Although the particle size of the collected dust has been reported, the particle-size distribution of the suspended dust at industrial sites has not yet been reported. Correlation between the particle-size distribution of dust in unsuspended and in the dispersed state in a dust cloud also has not been established. Large variations in particle-size distributions are expected from dust agglomeration.

Dust Cloud Generation

Factors that affect generation of a dust cloud are the number and kind of chemical components and their concentrations, particle-size distribution of dust in the condensed state, particle-size distribution, and concentration of dust in the dispersed state. The explosive properties of dust are related to the explosive properties of its components. Creating a grain dust cloud depends on dust generated from the grain kernels and evolution of the dust from the grain mass into the air to form a cloud. Generating dust from grain is related to the susceptibility

[2] Mention of firm names or trade products does not constitute an endorsement by the U.S. Department of Agriculture over others of a similar nature not mentioned.

of the grain to abrasion or breakage as it is handled and to the stress applied to the grain. The evolution of a dust cloud depends on the character of the dust, type of grain, and method of handling. Entrainment of dust from a dust layer or pile into an airstream is related to flow characteristics of the dust, shape of the dust pile, and instantaneous velocity of the air stream. Cloud permanence is related to the settling velocities of individual particles, air velocity, turbulence, and flow path.

Generating dust in corn during handling was studied by Martin and Stephens (1977). They found that the percent of breakage was directly related to the number of times the grain was handled. Total weight of dust collected by the dust-collection system increased by 0.002 percent per handling, but the weight of fine dust (diameter <125 μm) collected by the dust-collection system was relatively constant at 0.03 percent of the grain handled. Stephens and Foster (1976) found a correlation between susceptibility to breakage of corn and breakage experienced during handling. Methods of determining the susceptibility to breakage of corn were reviewed by Sharda (1977).

Mechanisms for evolution of dust from grain, settling of dust onto the floor, and redistribution or entrainment of dust from the floor to the air stream have yet to be determined. However, some experimental and theoretical studies have been carried out on entrainment of coal dust in turbulent air and on entrainment by shock wave distribution. Singer and others (1969) reported that the minimum entrainment velocity of dust depended on the geometry of the pile, cohesiveness, bulk density and compaction, adhesive nature of the surface, and vibrations perturbing and supporting the surface. The experimental air entrainment velocity was a function of particle size and was minimal at a diameter of 30 μm. Dust dispersal (minimum local velocity for dispersal of dust ridges) was affected by preconditioning the dust layer with air at a relative humidity above 75 percent. Singer and others (1972) developed a semi-empirical expression to relate the minimum air velocity (eqn. [3]) and dispersion rates (eqn. [4]) of coal dust to the geometry, cohesion, porosity, and bulk density of the dust pile.

$$U_L = aL^b A^c (\rho_B S_c)^d \quad [3]$$

where

U_L = local velocity at midheight of the dust pile for threshold dispersion, m/sec
L = base length of the pile in the direction of air flow, cm
A = leading angle at the base of the dust pile, degrees
ρ_B = bulk density, g/cm³
S_c = yield shear stress, dynes/cm²
a,b,c,d = empirical constants

$$E_n = 0.121\ U_L^{2.1} \rho_B^{5.9} \quad [4]$$

where

E_n = entrainment rate, g/sec.
U_L = local velocity at midheight of the dust pile for threshold dispersion, m/sec
ρ_B = bulk density, gm/cm³

Minimum entrainment velocities of 5 to 30 m/sec for coal dusts were reported; rock dust mixed with coal dust was entrained at ratios that were similar to the ratios in the dust layers. Hwang and others (1974) developed a mathematical model for dust entrainment caused by an explosion-induced turbulent airflow. Both rectangular and circular ducts were examined. A relation between cross-stream and down-stream dust concentrations as a function of time was presented for a rectangular duct (eqn. [5]).

$$c = \frac{Q}{2abL}\int_0^{t_d}\left[\operatorname{erf}\left\{\frac{z - U(t-t_1)}{2\sqrt{k(t-t_1)}}\right\} - \operatorname{erf}\left\{\frac{(z - L - U(t-t_1)}{2\sqrt{k(t-t_1)}}\right\}\right]\cdot$$

$$\left[1 + 2\sum_{n=1}^{\infty} e^{-km^2\pi^2(t-t_1)/a^2}\cos\frac{m\pi x}{a}\cos\frac{m\pi x_1}{a}\right]\left[1 + \sum_{n=0}^{\infty}\frac{2b}{n\pi(Y_b - Y_a)}\cdot\right.$$

$$\left. e^{-kn^2\pi^2(t-t_1)/b^2}\left\{\sin\frac{n\pi Y_b}{b} - \sin\frac{n\pi Y_a}{b}\right\}\cos\frac{n\pi y}{b}\right]dt_1. \quad [5]$$

where

a = height of rectangular duct
b = width of rectangular duct
c = dust concentration, milligrams per liter air
k = diffusion coefficient
L = dust-bed length in axial direction
m = empirical constant
n = distance in the direction normal to a boundary
Q = mass rate of dust production from a surface source
t = time
t_d = time at which the dust-lifting process is completed
U = convection velocity

x,y,z = Cartesian coordinates (x, y, and z are height from floor, distance from side wall, and downstream distance, respectively)
1 = location of instantaneous source

Singer and others (1976) reported results for large-scale tests of dust entrainment caused by explosion-induced airflow. The entrainment velocities for steady-state airflows were similar to the air velocities for explosion-induced airflows. Wetted and wetted-and-dried layers of coal dust on rock dust dispersed faster than untreated layers because of the selective lifting of relatively large briquetted fragments that dispersed in the airstream. Eckhoff (1976b) defined the dispersibility of dust powder as "the ease with which particles in the powder are distributed in a continuous, viscous medium so each particle is completely surrounded by the medium and does no longer make permanent contact with other particles." This definition is not easily applied in practice. Nevertheless, he did discuss the important factors that affected the dispersibility. These factors, in order of importance, are particle material, particle size, particle shape, degree of compaction, humidity of the ambient medium, mechanical treatment to which the powder has been subjected prior to the dispersion process, and added liquid.

Distribution of dust by a shock wave was used by Seeker and others (1978) to study the kinetics of coal combustion in a shock tube. The dust was dispersed and preheated by the incident shock wave and ignited by the reflected shock wave. Currently, these techniques are being applied to studies of grain dust (Vaughn and others 1978).

The settling rate of dust from dust clouds is related to particle size, difference in density between the particle and air, and air velocity. The theoretical velocity for settling of spherical particles in still air has been calculated by Matkovic (1977), who plotted the log of the terminal velocity versus the log of the particle diameter for dust particles of various specific gravities in air under the standard condition (273° K, 1 atm). For a particle with a specific gravity of 1.5, the velocity of a 3 μm diameter particle was 2.5 cm/min and for a 50 μm diameter particle, 625 cm/min. When the velocity of the airstream increased above the entrainment velocity, dust particles remained in the air stream and would not settle out.

An obvious lack of information concerning dust cloud characterization lies in measurement of the *in situ* particle-size distribution and concentration of a dust suspended in a cloud. Eckhoff and Fuhre (1975) developed an optical density system for concentration measurements in grain dust clouds. The system was first calibrated in a pilot dust cloud generator and subsequently installed in a grain elevator. Results obtained by these workers confirm the difficulties in optically measuring dust concentration without simultaneously measuring particle-size distribution because of problems in reproducing the degree of dust dispersion in the actual plant that were present in large-scale or pilot plant experiments. In a recent report, Hertzberg and others (1978) used the principle of optical density to measure dust concentration in dust clouds. By assuming a certain value of the extinction constant, which is a function of the particle-size distribution, they attempted to specify the degree of particle agglomeration in the dust cloud. The influence of variation in particle-size distribution from aggregation, and selective settling in combustion, can be measured only if the particle-size distribution is measured simultaneously with the light extinction measurement of concentration.

Significant progress has been made in analyzing dust generated from grain breakage during handling. Alternate methods of grain handling, grain conditioning or grain drying, methods of avoiding evolution of grain dust from the grain mass, and methods of controlling evolved dust must be improved.

Causes and Effects of Grain Dust Explosions

Dust Combustion Without Explosion

If a pile or layer of combustible dust is ignited without stirring or mixing with air, the dust is not likely to explode. This is because the amount of oxygen that can permeate void spaces in the dust is limited; consequently, the combustion rate is limited and the dust merely

will smolder. Oxygen permeating into burning dust is a result of rising hot combustion gases. Similar airflows have been studied in moisture transfer in soils. For instance, Farrell and Larsen (1973) studied oscillatory airflows in aggregated media that were produced by turbulent airflow over soil surfaces.

If the heat required to raise the temperature of a dust mass to its ignition temperature is less than the quantity of heat released by the dust combustion minus the heat loss to the surroundings, the dust will smolder or burn slowly. If the burning dust forms a cavity in the center of the pile caused by the creation of dense ash and loss of gaseous combustion products, dust may collapse into the cavity. As dust falls into the cavity it could mix with air and produce an explosive dust concentration that will result in explosion.

Heated grain dust generates pyrolysis gases. Heat released by a smoldering dust layer could pyrolyze the upper dust layers. A mixture of combustible pyrolysis gases would then rise from the surface of the dust. If the surface of the dust is disturbed so the burning dust contacts a dust mixture and combustible pyrolysis gases and air, then an explosion or flash fire is possible.

Extensive studies on dust pile combustion have been conducted by many researchers (Bowes and Townshend 1962, Palmer and Tonkin 1957, Palmer 1957, Ho 1969, Welker 1970, Grewer 1971, Chiotti and Morris 1978). Welker (1970) reviewed the pyrolysis and ignition of cellulosic materials. At temperatures between 200° and 280°C, an endothermic pyrolysis generates carbon dioxide, water vapor, and acetic acid. At temperatures between 280° and 500°C, a cellulosic material generates carbon monoxide, hydrogen, methane, carbon dioxide, acetic and formic acids, ethanol, aldehydes, ketones, and tars. At temperatures above 500°C in inert atmospheres no appreciable reaction takes place, but the remaining char will be consumed if oxygen is present. Welker (1970) also discussed the radiant ignition of cellulosic materials, ignition delay, and several mathematical models describing ignition of cellulosic material.

Grewer (1971) discussed several experimental instruments used to measure the autoignition temperature of a dust layer. Types of airflow used in these instruments included horizontal airflow over the sample surface, vertical tubes with flow through the sample, or vertical tubes with airflow around a basket containing test samples. Each device provided only relative values of the ignition temperature.

Chiotti and Morris (1978) studied the low temperature (100° to 225°C) pyrolysis of grain dust in an attempt to develop a detector for pyrolysis. A vertical tube furnace with air passing through the sample was used. The major product liberated from corn starch, meal, and kernels; milo and oat dust; and confectioner's sugar at temperatures between 120° and 200°C was water with small amounts of carbon dioxide, carbon monoxide, and hydrogen. At temperatures between 190° and 200°C, the consumption of oxygen increased. Significant amounts of hydrogen were released from the pyrolysis products after available oxygen was consumed. It is not certain whether the hydrogen concentration would be high enough, when mixed with air, that a flammable or explosive mixture would result.

Combustion of dust layers heated from below was approached as a problem in chemical analysis by Chiotti and Morris (1978). With this approach lies the hope of correlating the extensive work on combustion of pure dust combustion to hybrid combustion. Three possible ignition schemes can be envisioned:

1. ignition of a pure dust cloud
2. ignition of a pure gas or a mixture of gases
3. ignition of a mixture of dust and gas, or hybrid combustion

A significant problem can be foreseen in the analysis and detection of an explosive hybrid mixture. If a method for measuring dust concentration by light extinction is used, the concentration of the combustible gas will not be measurable. If hybrid ignition is determined as a significant ignition mechanism, multiple detection devices may be necessary.

The combustion of dust layers on heated surfaces is reasonably well understood; and the effects of layer thickness, porosity, and ambient oxygen concentration have been identified. However, the effect of pyrolysis gases generated over a heated dust layer on the dust's

minimum ignition concentration has not been determined.

Flammability of Mixtures of Vapors, Gases, and Dust Clouds

The theory of gaseous reactions is well established. Chemical reactions have been proposed to explain the first and second limits of many gaseous mixtures (Lewis and von Elbe 1961). One conclusion from analyzing gaseous reactions is the importance of the combustion chamber wall in progression of the reaction. The ratio of exposed solid surface area to volume of gaseous components, and the physical characteristics of the solid surface of the combustion vessel, are related to wall-induced reactions. The importance of the wall and the influence of turbulence in the mixture have made practical application of theoretical analysis using chemical reactions less useful.

Coward and Jones (1952) published an extensive experimental study and literature review of the flammability of single gases and vapors. It was arbitrarily assumed that the mixture of a single flammable vapor and an oxidizing gas should develop a flame for a prescribed distance. Altering this distance changed the experimental result.

Hertzberg (1976) presented a possible explanation of a lower flammability limit (LFL) and an upper flammability limit (UFL) for single flammable gases. They were determined by natural convective flow or buoyancy effects, conductive and convective heat losses to the walls, radiative heat losses to the surroundings, mixing by selective diffusion, and nonlaminar flow gradients (flame stretch).

Zabetakis (1965) extended the work of Coward and Jones (1952) to include flammable gas mixtures at various oxygen concentrations. For mixtures of several flammable vapors, the LFL could be estimated according to Le Chatelier's law. This law denotes a linear relation between the LFL of a mixture of flammable gases and the LFL and concentration of each flammable component in the mixture measured by itself. Le Chatelier's law states that if two gases are present in a mixture at concentrations equal to one-half of their respective LFL, the mixture will be flammable. Hilado and Cumming (1977) confirmed experimentally the results of Zabetakis (1965) for the flammability of pyrolysis products from plastic materials.

A possible extension of Le Chatelier's law is the calculation of the UFL. If the limiting oxygen concentration in a mixture is considered, an expression can be determined for the UFL of a gas mixture by noting the limiting oxygen concentration of the respective single gases or vapors. Reasonable agreement is found between the experimentally determined upper flammability data of Hilado and Cumming (1977) and the estimated UFL.

Pace (1977) estimated the UFL and the LFL of flammable vapor mixtures in aircraft gun compartments. The flammability estimates were used to determine airflow requirements for diluting combustible gases. An extension of Le Chatelier's law was used to include the effects of inert gases.

The influence of flammable gases in dust-air mixtures and hybrid mixtures on dust cloud minimum ignition energy, minimum dust concentration, and rate of pressure rise has been studied by several researchers. Data of Nagy and Portman (1961) indicated a linear relationship between the LFL of a mixture of coal dust, methane, and air and the LFL of coal dust-air and methane-air. Anthony (1977) found a similar relationship (Le Chatelier's Law) between the minimum flammable concentration of polyvinyl chloride-air, methane-air, and of polyvinyl chloride, methane, and air. Anthony (1977) also determined that the minimum concentrations of polyvinyl chloride-air were affected strongly by temperature. However, the linear relation between the LFL of the constituents and that of the mixture still was valid.

Nagy and Portman (1961) found that the rate of pressure rise for coal dust alone could be increased by increasing the induced convection. However, if the induced convection was increased too much, the rate of pressure rise decreased. When 2 percent methane was present and the coal dust-methane-air cloud was subjected to increased turbulence, the rate of pressure rise continued to increase without limit.

Bartknecht (1977) reported that the rates of pressure rise for explosive mixtures of dust,

flammable gas, and air were larger than those for an explosive dust-air cloud. He also reported that mixtures of explosive dust-air and flammable gas-air ignited at concentrations less than those needed to ignite single flammable materials. Ignition energies for hybrid mixtures were less than those for single flammable component-air mixtures. Reay (1977) suggested that if flammable gas concentrations exceeded 0.2 percent in explosive dust clouds, the mixtures should be treated as flammable gases and not as dust clouds. If the rate of pressure rise is greater for the explosion of a mixture of flammable gas-dust-air than a mixture of dust-air, the reaction rate probably has increased. Because the most likely limiting condition for a sustained dust-air detonation is the reaction rate, one might expect that a flammable gas-dust-air mixture would detonate more easily than a dust-air mixture.

The effect of flammable gas mixtures on minimum flammable concentration of the mixture has been determined for several gas mixtures. Only in a few cases have trace quantities of a component drastically altered the flammable limits of the mixtures; for example, the effect of trace moisture on the flammability limits of oxygen-carbon monoxide. The effect has been similar for flammable gases on the minimum explosible concentration of dusts. In those dusts and flammable gases that were studied, a linear relation was found between the concentrations of dust and the flammable gas and the LFL of the mixture. In none of the studies did a trace component alter the minimum explosible concentration of a dust cloud.

Detonation in a Dust Cloud

The two basic types of explosion phenomena are deflagration and detonation. In an ideal deflagration, the flame speed is subsonic. Within an enclosed space, pressure equalizes at the speed of sound. Because the flame speed is less than sonic velocity, the pressure is the same throughout the enclosed space. Pressure will, of course, increase as the explosion progresses.

The flame speed of a deflagration can be modeled using heat transfer mechanisms of conduction and radiation (see **Theoretical Analysis of Dust Explosions**). The flame front heats the unburned gas, or dust, that burns and forms the flame front. Flame speeds have been predicted as high as 1.5 m/sec.

Flame speed of a steady state detonation is supersonic. Propagation of a detonation is characterized by a steep pressure increase. One fundamental difference between deflagration and detonation concerns the distribution of pressure in the vessel. Pressure in a deflagration at a given instant is uniform throughout the vessel; in a detonation, a discontinuity in pressure is developed in front of the flame. Flammable gases, or dust, in front of the pressure wave are heated by passage of the wave to an autoignition temperature. Energy released by resulting combustion sustains the pressure wave.

Research on detonation of gases and vapors has been summarized by Lewis and von Elbe (1961). Detonation velocity agreed closely with predicted theoretical values of the sum of the acoustic velocity of a warm gas behind the wave front and particle velocity of combusted gases.

Explosion wave velocities in controlled experiments with dust clouds approached those of a theoretical detonation (Nettleton 1977). Table 1 summarizes information on dust cloud detonations in large vessels. Combustion waves were developed in a tube or channel with a large length to diameter ratio ($L/D > 50$). The pressure developed by the combustion wave exceeded 10 atm.

Bartknecht (1978b) found that the maximum speed of a combustion wave was related to both the length of the combustion chamber and the K_{st} value for the dust. The K_{st} value for a combustive mixture is defined as the maximum rate of pressure rise multiplied by the cubic root of the volume in which the maximum rate of pressure rise was measured. The "st" indicates that the K value is for a dust. It is an abbreviation derived from the German word "staub." Dust with a low K_{st} value could develop a combustion wave with a velocity of 2,000 m/sec if the vessel were long enough. Bartknecht also found a reasonable correlation between explosion pressure and the K_{st} value for dust. When the tube length was doubled, maximum explosion velocity approximately doubled until a velocity of 2,000 m/sec was achieved. Bart-

TABLE 1.—*Possible detonations in dust clouds*

Researcher	Dust type	Precombustion gas	Type of dispersion	Vessel		Type of combustion	Ignition source	Maximum explosion velocity	Maximum pressure	Method of determining detonation
				Area	Length					
				m^2	m			m/s	atm	
Strauss (1968)	Aluminum powder d = 40 μm Ave.	Oxygen	Predispersed cloud	5.47×10^{-4} (circular)	2.7	Closed to open	Exploding silver wires	1,600	34	Flame velocity
Nettleton & Sterling (1973)	Coal dust volatile material = 30 percent dust diameter 78 percent ≤ 76 μm	Oxygen	Predispersed cloud	4.41×10^{-3} (circular)	8	Closed to open	Electric spark	1,500	—	Occurrence of second flame front
Cybulski (1971)	Coal dust 1st 10 m of gallery 80 percent < 75 μm Next 190 m of gallery 25 percent < 75 μm 12.7 percent ash 4.3 percent hygroscopic water 2.5 percent free water	Air	Dust on floor	2.4 (rectangular)	400; Only one-half of vessel was used in explosion	Ignition in center of 400 m vessel propagated to closed end	750 g blasting powder in a mortar	2,000	52 (est.)	Flame velocity
Wojcicki & Zalesinski (1973)	Coal dust 93 percent ≤ 30 μm	Oxygen	Predispersed cloud	2.5×10^{-3} (square)	3.5	Closed to open	350 J discharged thru exploding foil	1,600	—	Occurrence of second flame front
Richmond & Liebman (1974)	Coal dust 80 percent < 74 μm	Air	Dust laid on shelves and ribs near roof	5.6 (rectangular)	600	Closed to open	10 ft long zone of 7 percent natral gas-air mixture	487 (does not include particle velocity)	20	—
Rae (1972)	Coal dust volatile material = 36 percent 85 percent ≤ 63 μm	Air	Dust laid on floor	5.6 (rectangular)	366	Closed to open	Captive rockets	1,300	14.5	—
Bartknecht (1978[b])	Coal dust	Air	Dust injected along tube length from several pressurized containers (25 bars)	0.126 (circular)	40	Closed to open	Jet of flame	700	10	—
Bartknecht (1978[b])	Pigment dust	Air	"	0.126 (circular)	40	Closed to open	Jet of flame	2,000	25	—

knecht's (1978b) data indicated that for the dusts with K_{st} values greater than 600 (bar-m)/sec a constant velocity was attained (2,000 m/sec) by using 20-m and 40-m tube lengths.

To protect a structure from an explosion by venting, suppression, or active inerting, the maximum speed of the flame and pressure fronts should be known. Presently, available data indicate that high velocity and high pressure combustion dust waves can develop in an enclosed space. A theoretical explanation of these waves as detonations has not yet been proven. When ignited, explosions of common dust, such as coal dust suspended or distributed on the floor, have generated combustion waves with velocities exceeding 1,000 m/sec and pressures over 10 atm (Bartknecht 1978b).

Experimental analysis is needed on the effect of trace gases on detonability of a dust cloud. One simple explanation that secondary grain elevator explosions are more damaging than the primary explosion is that first, the primary explosion, which is most likely a deflagration, releases heat to the dust cloud and pyrolyves the dust to noncondensable flammable gases and vapors; second, the primary explosion is likely to be oxygen limited, in other words, the primary explosion slows down because of an oxygen deficiency so the pyrolyzed gases are not completely burned; and third, a mixture of flammable gas and dust in a cloud, when ignited, can develop into a steady detonation. This series of events could easily be duplicated experimentally in a large scale explosion chamber. Steady detonation does not seem very likely in industrial plants because insufficient structural strength would not allow pressure buildup. However, high speed deflagrations can develop.

The ramifications of a possible detonation in a grain elevator explosion are widespread. It could require redesign of most explosion detection, venting, and suppression systems. In addition, theoretical models of minimum explosible concentration, flame propagation, and minimum ignition energy must be rederived. Even the experimental measurement of the minimum explosible dust concentration must be made. Before the development of grain dust explosions can be understood, it will be necessary to study them on a large scale. This will yield useful data necessary for analyzing and preventing explosions.

Measurement of Dust Cloud Explosibility

Dust explosibility studies have been conducted by the Bureau of Mines since its establishment in 1910. Investigating explosibility of agricultural dust was initiated there, transferred in 1917 to USDA's Bureau of Chemistry and Soils, and transferred in 1936 back to the Bureau of Mines for investigations of agricultural, industrial, and other types of dusts. About 1970, this work was phased out. During the active period, supplementary equipment and procedures were developed to evaluate factors affecting ignition and explosibility of all types of dust, and a method was developed for preventing explosions (Jacobson and others 1961; Nagy and others 1950, 1964a, 1964b, 1965; Nagy and Surincik 1966).

The explosibility index, E, as defined by the Bureau of Mines is shown as follows:

$$E = \left(\frac{T_{mn,c}}{T_{mn,d}}\right)\left(\frac{C_{mn,c}}{C_{mn,d}}\right)\left(\frac{P_{mx,d}}{P_{mx,c}}\right)\left(\frac{P'_{mx,d}}{P'_{mx,c}}\right) \qquad [6]$$

where

$T_{mn,c}$ = minimum ignition temperature of a Pittsburgh coal dust cloud
$T_{mn,d}$ = minimum ignition temperature of the dust cloud tested
$C_{mn,c}$ = minimum explosible concentration of a Pittsburgh coal dust cloud
$C_{mn,d}$ = minimum explosible concentration of the dust cloud to be tested
$P_{mx,c}$ = maximum pressure developed by a Pittsburgh coal dust cloud in the Hartmann apparatus
$P_{mx,d}$ = maximum pressure developed by a dust sample for a dust cloud in the Hartmann apparatus
$P'_{mx,c}$ = maximum rate of pressure increase developed by a Pittsburgh coal dust cloud
$P'_{mx,d}$ = maximum rate of pressure increase developed by a dust cloud

Measurements, other than the explosibility index, were performed on cornstarch and included relative flammability (90 percent), percent oxygen required for explosion (5 percent), and the effect of moisture content and particle size on the explosibility index. Dorsett (1960) reported that the maximum explosion pressure was reduced from 6.5×10^5 pa to 2.1×10^5 pa when the

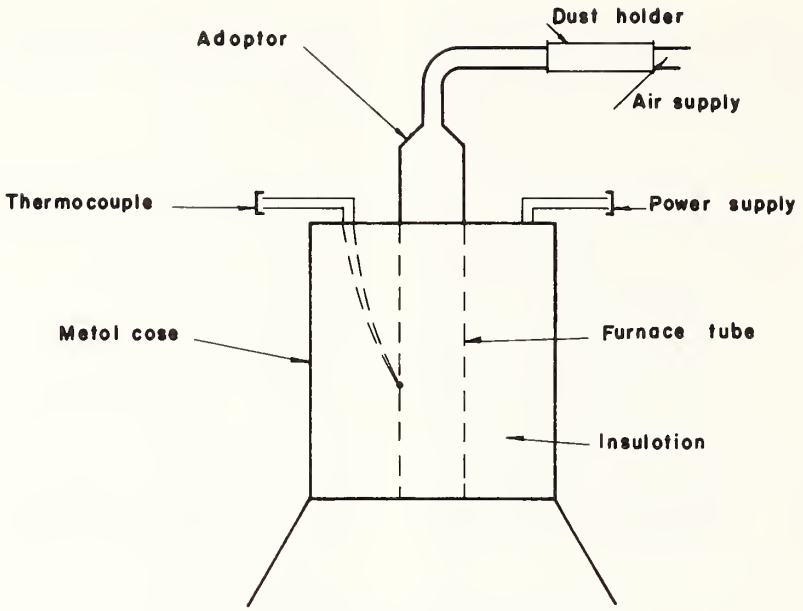

Figure 2.—Godbert-Greenwald furnace.

moisture content was increased from 0 to 23 percent. They reported that the ratio of explosibilities of two samples of the same dust was equal to 1 over the cubic root of the respective average particle diameters (Jacobson and others 1961). Tests were also made of minimum ignition temperature (400°C) and energy (0.3 J) for layers of cornstarch.

Measurements of dust cloud combustibility at the Fire Research Station, Borehamwood, England, were obtained from three tests, which determine the ability of a dust to propagate a flame (Palmer 1973). These tests involved upward ignition by an electric spark or heated coil in a vertical tube similar to the lucite Hartmann bomb, ignition by a heated wire in a horizontal tube, and downward ignition by an electric spark or hot wire in a vertical tube. When a dust was shown to be flammable, a set of tests similar to those of the Bureau of Mines was conducted. These tests included measuring minimum ignition temperature and maximum oxygen concentration without explosion as determined by a modified Godbert-Greenwald furnace, minimum explosible dust concentration and minimum ignition energy in the vertical lucite Hartmann bomb, and maximum pressure and maximum rate of pressure rise in the steel Hartmann bomb.

Researchers at the Federal Institute for the Testing of Materials, Dahlem, Berlin, West Germany, conducted experiments measuring the possibility of dust explosions. Such characteristics as flame size and violence of reaction based on observation and photographs of the explosion of a 10 cm^3 dust suspension were determined in the presence of a gas flame.

The minimum ignition temperature was determined by blowing a dust sample into a temperature-controlled horizontal cylinder against a vertically mounted concave disk. Temperature sensors were located in the cylinder wall and in the disk face. The maximum pressure rise and the maximum rate of pressure rise were measured in an apparatus similar to the steel Hartmann bomb. Flammability of a dust layer was determined by igniting the layer with a Bunsen burner flame, a lighted match, the glowing end of a cigarette, or a hot glass rod. Burning speed of the dust surface and character of the burning dust were recorded. Minimum ignition temperature of a dust layer was determined by heating the dust exposed to air at room temperature. The ignition temperature of dust layers was determined by heating the dust in a furnace, regulated so the temperature of the dust and the air around it were approximately the same. The flammability of pyrolysis gases pro-

duced by a combustible dust was assessed by determining whether the gases evolved from a heated test tube of dust-supported combustion. If combustion occurred, maximum pressure and maximum rate of pressure increase were determined for the combustion.

A group of chemical manufacturers in West Germany devised four experiments to assess dust explosion and fire hazards (Palmer 1973). Flammability was determined by

1. putting a 500°C platinum wire into a pile of dust
2. determining the ignition temperature of a pile of dust on a controlled temperature surface
3. measuring the temperature at which the dust starts to decompose
4. determining sensitivity of the dust to shock compression by a drop hammer test. If dust sparks, flames, or explodes, the dust is considered to be shock sensitive

Eckhoff (1976a) and Hay and Napier (1977) questioned the values of the minimum ignition energy determined by the Bureau of Mines test procedure. Only voltage and capacitance used to generate the spark were considered in calculating minimum ignition energy. Losses occurred in transforming a low voltage to a voltage higher than the breakdown voltage. The possibility of incomplete capacitor discharge and the effect of varying voltage and capacitance to obtain similar ignition energies were ignored in calculating the minimum ignition energy. A more accurate measurement of the minimum ignition energy can be obtained by measuring the voltage and the current across the spark gap and by integrating their product over spark duration.

In addition to demonstrating the difficulty of calculating the minimum ignition energy, Eckoff (1976a) showed that the duration of the spark affected the minimum ignition energy. Under short duration, high voltage sparks created a high pressure pulse, pushing dust particles away from the spark gap and decreasing the dust concentration in the high temperature zone of the spark gap. Adding a resistance in series with the spark gap to increase the discharge time created "soft" (low voltage) sparks that ignited dust clouds at energies much lower than short duration "hard" (high voltage) sparks. These measurements and findings were confirmed by Hay and Napier (1977).

A brief review of the history and problems of igniting agricultural dust clouds by mechanical sparks was presented by Morse (1958). He also developed several tests for igniting a dust cloud by a mechanical spark having an input energy of 576 J.

Igniting coal dust clouds by sparks from impact of a steel pipe on such hard minerals as sandstone, limestone, and pyrite-bearing limestone was investigated by Kelley and Forkner (1976). Coal dust clouds at concentrations as high as 300 g/m^3 were not ignited by the steel pipe-rock impact, but addition of 1 percent methane by volume allowed the mixture to ignite. No ignition occurred when the tangential collision velocity was less than 4.57 m/sec. Ignition was not originated by sparks but by the "hot friction induced smear" on impacted rock at the impact site.

Influence of trace concentrations of flammable gases and vapors on ignition characteristics of dust clouds is extremely important. Minimum ignition temperature, minimum explosible concentration, and pressure effects are altered by the presence of small concentrations of flammable gases. Research on ignition characteristics of hybrid mixtures of dust clouds and flammable gases was discussed earlier in this review (*see* **Causes and Effects of Grain Dust Explosions**—Flammability of Mixtures of Vapors, Gases, and Dust Clouds).

Enomoto (1977) developed a rotating cylinder with a ribbed interior wall designed to obtain a uniform dust concentration before measuring maximum pressure and rate of pressure change in dust explosions. Ribs in the wall picked up dust and dropped it into the center of the rotating cylinder. By carefully controlling the speed of cylinder rotation, uniform dust clouds were generated. Uniformity of the dust cloud was measured by noting variation of extinction of a light beam that was passed axially through the rotating cylinder. When the dust cloud uniformity was measured, the normal steel ends of the cylinder were replaced with transparent covers to allow a light beam to pass through the dust. A problem with this apparatus is that dust particles in the cloud are probably agglomerates. Unfortunately, the dispersion mechanism will not deagglomerate these clumps

of particles. When only extinction is measured, effects of agglomeration of particles cannot be determined. The procedure could be improved by measuring the particle-size distribution of particles in the dust cloud.

Work of Eckhoff (1976a), Hay (1977), Enomoto (1977), and Hertzberg and others (1979) has laid the foundation for developing fundamental methods of testing and analyzing dust. The excellent work by Hertzberg and others (1979) represents a great step forward toward a proper method of measuring the minimum explosible dust concentration. Similar work has recently been carried out by Eckhoff (1978a). Previous tests provided only relative values of explosibility. The new approaches should be extended to all basic characteristics of the dust cloud, the explosive atmosphere, and the explosion. The time has come to use the fundamental equations of momentum, heat, and mass transport to describe the phenomena that occur.

One of the experimentally difficult tasks yet to be overcome is establishing a uniform, steady state, dust cloud. The rotating drum apparatus of Enomoto (1977) appears to be promising, but even with it, measurement of dust concentration and particle-size distribution must be refined. The apparatus demonstrated poor dust dispersions with cohesive powders. The large tube apparatus described by Palmer (1973) and the apparatus used by Eckhoff (1978a) appear to be good dust distributors for steady state work.

Static Electrification and Dust Explosion

Static electricity has been reported repeatedly as a possible ignition source of dust explosions. In this section, we will review papers on ignition of a dust cloud by a direct current spark, static generation in dust clouds, on surfaces of belts, and in grain-handling equipment and neutralization of static electricity on equipment, dust clouds, and in flowing bulk solids.

Dust cloud ignition

Igniting a dust cloud by a direct current spark has been reported by several authors (Dahn 1978, Dorsett and others 1960, Jacobson and others 1961). Characterization of an incendiary spark was reported by Eckhoff (1976a) and Hay and Napier (1977). In both of these studies, the current and voltage versus duration of the spark were measured and were used to calculate the minimum ignition energy of the dust cloud. These studies determine minimum voltage and current required to ignite a dust cloud. Since a static discharge is nothing more than a direct current spark, it is possible to predict what static charges are incendiary.

Static electricity generation

When two materials come in contact and separate, electrons can be transferred between the materials. One of the two materials will have a net excess of electrons and a negative charge, the other, a deficiency of electrons and a positive charge. If the rate of static charge generation is greater than that charge depletion from conduction to an electrical ground or from combination with an ion of opposite polarity, the number of electrons or electron holes (absence of an electron) will increase until the breakdown voltage of the air is reached. When the breakdown voltage of the air is reached, the air between the charged solid and a second solid (with a voltage differing from the first solid by the breakdown voltage) will ionize, and electrons will travel between the solids.

Bright (1977) reviewed the static electrification of flowing liquids and solids. He considered restricting the solid velocity in flowing solids to eliminate excessive charging by keeping

$$i_s < 2.7 \times 10^{-5}\ d\ v \qquad [7]$$

where

$i_s = 1/4\ c\ \pi\ d^2\ v$
$c = 1.04 \times 10^{-5}\ \rho_p^{0.73}\ v^{2.15}$
ρ_p = powder density (kg/m^3)
v = velocity
d = pipe diameter
e = charge density
i_s = streaming current

Bright (1977) also suggested that the streaming current i_s could be reduced by selecting proper pipe material (for flowing dusts and solids) or by neutralizing the charge. Material selected for the pipe should minimize the difference between the zeta potential of the pow-

der and that of the pipe as suggested by Pratt (1978). Neutralization of the charge can be accomplished by electrical and nuclear means as discussed in the next section on static electricity neutralization.

Eichel (1967) discussed the origin and nature of electrostatic phenomena and provided methods for calculating the magnitude of generating static electricity by movement of a low-conductivity fluid. Although concern was expressed for the static charge generated by flow of a liquid, the principle of generating an electrostatic charge by flowing dust or powder may not be identical.

Electrification of a gas-solid suspension flowing in steel and insulation-coated pipes was experimentally studied by Masuda and others (1976a, 1976b). The current generated on insulation-coated pipes was higher than the current generated on a steel pipe. The current was found to be proportional to the powder flow rate, and the mean air velocity to the power 1.4 to 1.9, but inversely proportional to the mean particle diameter.

Static electricity neutralization

Static electricity is generated by contact and separation of phases. Therefore, reducing flow rates, avoiding free fall and splashing, and reducing the rate of separating material having different dielectric constants can reduce the accumulation of electrostatic charges during processing, transfering, and storing of materials. The following is a brief summary of each method of controlling electrostatic charges.

Grounding and bonding.—Static charges can be neutralized on large pieces of equipment by grounding all parts of the equipment. In a conveyor system, conductive grease should be used in idler roller bearings. The main frame of the system should be connected to a grounded cable.

Using a conductive conveyor belt was questioned by Bradford (1977). His preliminary research indicated that discharge from a conductive conveyor belt might be more incendiary than that of a nonconductive conveyor belt because of an instantaneous charge migration that was possible in a conductive belt, which allowed a discharge of large currents by means of a spark.

Ionizing surrounding atmosphere.—Static charges can also be neutralized by electrical and nuclear means (Beach 1957). The electrical neutralizers can be either active or passive. The active static neutralizer consists of a set of high voltage needles that generates corona ionization of the surrounding air. The polarity of that ionization is determined by the polarity of the voltage on the needles. A passive electric neutralizer consists of grounded needle points, or static tinsel. These points act as corona discharge centers. The voltage potential necessary for the ionization is obtained from the static electrified surface that is being neutralized. Another type of static neutralizer is the nuclear type. A nuclear static eliminator uses the emission of alpha particles from decay of a nuclear source to generate ionized air. As the alpha particles are emitted from the source, they hit air molecules, which then ionize. Both polarities of ions are produced in this ionization.

Providing time for relaxation.—An enlarged section of pipe can provide the time necessary to reduce the charge to a safe level before the material is discharged into a vessel (Eichel 1967).

Increasing electrical conductivity.—Conductivity of the material (grain or powder) can be greatly increased by adding a minute amount of additives. Charges produced in treated material may be effectively conducted to a metallic ground (Eichel 1967).

Humidifying surrounding atmosphere.—Increases in relative humidity (60-70 percent RH) can increase the amount of water film on nonconducting solids. These films, coupled with traces of dissolved impurities, can provide conductive paths to dissipate charges.

Solid surface static electrification is a field of research that needs to be revived. Practical applications of the present charging theories need to be developed to reduce the possibility of spark generation in handling systems. In addition, the correlation between voltage and currents necessary for ignition of a dust cloud must be carefully compared to the voltage potentials and charge capacities that can be explained by static electrification.

Theoretical Analysis of Dust Explosions

Combustion processes encompass a wide range of physical phenomena. While the phenomena of a dust explosion might seem extremely complex, the physical principles that govern explosions are governed by the laws of hydrodynamics and thermodynamics. For idealized geometrics, it is possible to numerically solve the partial differential equations that describe the interaction of a dust cloud with an ignition source and the combustion wave, which might subsequently occur (Tanaka 1977, Smoot and others 1976). A theoretical model should be capable of describing physical phenomena of a system with a known original state and the contributing influencing factors to predict the state of the system at any time. Alterations in the described system's environment (venting, inerting, suppression) will alter the final outcome such as minimizing excessive overpressures.

Theoretical analyses of a dust explosion should predict the dust cloud ignition temperature; minimum ignition energy; minimum explosive concentration; velocities of particle, flame, and wave; pressure at any point in a vessel at any time; and the oxygen-concentration dependence of the system. Data needed for theoretical analysis include heat of combustion, chemical composition, dust moisture content, density, particle size, heat capacity, thermal conductivity, and dispersibility or interparticle forces such as electrostatic and particle friction for each type of grain dust. Also needed are *in situ* measurements of air temperature, relative humidity, dust particle-size distribution, dust cloud concentration, vessel shape and volume, and type of grain handled. Detailed knowledge of the chemistry of the combustion reaction is required, including both the proper chemical rate constants and diffusion coefficients. Essenhigh and others (1965, 1966) discussed the reaction kinetics of the problem.

Researchers tend to model specified aspects of dust explosion analysis in two steps. The first step involves dust cloud ignition. To ignite a dust cloud, thermal or chemical energy must be present, or added, and at least one dust particle must begin to react or combust exothermally. Mass, momentum, and energy balance around this particle will determine if the particle will continue to burn or be extinguished. If the first burning particle gives off enough energy to maintain its own combustion, and if it causes at least one other particle to combust, the cloud is ignited. The second step involves propagating the explosion. Since the second burning particle must ignite additional dust particles to form a flame front, the mass, momentum, and energy balances around a group of particles must be considered (Tanaka 1977). When energy released by a group of particles is greater than the sum of heat loss and heat required to elevate unburned particles to the ignition temperature, the flame will propagate.

Portions of explosion theory applicable to a grain dust explosion involve estimating the rate of pressure rise, the maximum pressure, and the required venting area for an explosion. Few papers (Palmer 1973) discuss the theoretical analysis of pressure development for dust cloud explosions in vessels, but much work has been done on the analysis of pressure development by a gaseous explosion.

Minimum Ignition Temperature

Ignition of a dust cloud has been theoretically modeled by several researchers. The ignition theory is divided into analysis of the minimum ignition temperature, the minimum explosive concentration, and the minimum ignition energy.

Minimum ignition temperature was studied by Nagy and others (1966), Cassel and Liebman (1959), Tanaka (1977), and Annamalai and Durbetaki (1977). Nagy and others (1966) used an energy balance around a dust cloud to determine the Semenov ignition temperature. It was reached when the heat loss from a reacting system to its environment equaled the heat generated by an exothermic reaction, and the derivatives of rate of heat loss and generated heat from the reaction with respect to particle temperature was equal.

The Semenov ignition theory implies that the proposed model (Nagy and others 1966) as-

sumes a uniform temperature throughout the dust cloud. The thermal heat loss by convection at the dust-cloud vessel surface disregards radiation. The most serious problems with Nagy's analysis are the formulations of heat loss and heat gain. Total heat loss is calculated by adding the heat accumulated by the dust to the heat lost by the dust cloud. This sum is multiplied by the difference between the furnace temperature and the reaction temperature and is inconsistent with the basic laws of heat transfer. In the heat gain equation, the effect of dust surface area is included in the exponential term of the Arrhenius rate constant expression and is inconsistent with the chemical reaction theory.

Cassel (1964) developed a model of single dust particle ignition by performing a heat balance around a single dust particle in an oxidizing atmosphere. He used the Semenov concept of determining the minimum ignition temperature of the particle. The minimum ignition temperature predicted by the model is given by equation [8]

$$T_{c,1} = \frac{K_c\left(\frac{\alpha-1}{\alpha}\right)}{r_p\left(\frac{1}{\alpha-2}\right)} \qquad [8]$$

where

$T_{c,1}$ = minimum ignition temperature
K_c = constant
r_p = radius of particle
$\alpha = \frac{E}{RT_i}$
E = activation energy
R = gas constant
T_i = reaction temperature

Cassel (1964) and Nagy and others (1966) ignored the radiation effects between the burning particle and its surrounding unburned particles and the vessel wall. Cassel (1964) mentioned of shielding by the cloud between the burning particle and the wall. The shielding would be more pronounced in large dust clouds, but this radiation effect was ignored.

Like Cassel and Liebman (1959), Mitsui and Tanaka (1973) assumed an energy balance about a particle; in addition, they included the radiation heat transfer between the burning and unburned particles. In a later paper, Tanaka (1977) included the radiation heat loss to the vessel wall. The temperature of the particle and the oxidizing gas surrounding the particle is determined by solving the following equations simultaneously.

$$\frac{6A'}{\sqrt{T_s}}\left\{\exp\left(\frac{E}{RT_s}\right)\right\} = \frac{12k}{D_p}(T_s - T_o) + \frac{\pi^{1/3}6^{2/3}B\rho_s D_p}{G_s^{1/3}C_d^{2/3}}(T_s^4 - T_o^4) \qquad [9]$$

$$6A'\left(\frac{E}{RT_s^{5/2}} - \frac{1}{2T_s^{3/2}}\right)\exp\left(\frac{-E}{RT_s}\right) = \frac{12k}{D_p}4(6)^{2/3}\pi^{1/3}B\rho_s\left(\frac{D_p}{G_s^{1/3}C_d^{2/3}}\right)T_s^3 \qquad [10]$$

where

$A' = A/\pi = C_g k_s Q$
$A = \pi C_g k_s Q$
B = radiation coefficient
C_d = concentration of dust
C_g = concentration of oxygen
D_p = diameter of particle
E = activation energy
G_s = mass of particles
k = thermal conductivity
k_s = reaction rate constant
R = gas constant
T_s = temperature of solid phase
T_o = ignition temperature
ρ_s = density of solid

If the essential data of the activation energy for the reaction rate coefficient, the pre-exponential factor for the reaction rate coefficient, the order of the reaction with respect to the solid and gaseous reactants, the heat of reaction, the emissivity of the particle, the gas and the vessel wall, the dust particle size, the gas thermal conductivity, and the particle density are known, equations [9] and [10] can be solved to determine the temperature of the particle and the gas surrounding the particle. Two areas of concern in this analysis are

1. the mathematical model may not adequately represent the physical phenomena taking place in the experimental apparatus used to determine the ignition temperature
2. much of the essential data may be difficult to obtain.

The experimental apparatus modeled by Tanaka (1977) and Mitsui and Tanaka (1973) is a modified Godbert-Greenwald furnace and is used to determine the relative ignition temperature of a dust cloud. The furnace was developed by Hartmann and Nagy at the Bureau of Mines (Hartmann 1957). This furnace consists of a wall with a controlled temperature and a vertical cylinder through which dust is blown downward by pressurized, unheated air. Tanaka (1977) envisioned a stationary dust cloud with a self-heating particle caused by internal reaction and inadequate heat loss from stagnant-surrounding gas. The dust cloud in the Godbert-Greenwald furnace is neither stagnant nor hot. Instead, cold, moving air surrounds the particles. The pressurized air stream flushes out much of the preheated air in the furnace so the cold air entering with the dust must be heated by the furnace wall. Ignition of the dust particle could occur if it strikes the surface of the wall.

The heat transfer mechanism explaining the ignition of a single particle on a heated surface is different from the one proposed by Tanaka (1977). Heat of combustion, particle size, emissivities, particle density, and thermal conductivity of the gas can be measured or estimated. However, the order of the reaction, pre-exponential factor, and activation energy require additional experimental measurements.

Annamalai and Durbetaki (1977) modeled the ignition temperature of coal dust as a homogeneous reaction. In their homogeneous gas phase reaction scheme, the volatiles were first evolved and then ignited. Van't Hoff's ignition criterion was used to determine the ignition temperature. The ignition criterion was met when the differential of dimensionless temperature, with respect to dimensionless bulk velocity, and the dimensionless bulk velocity equaled zero. Ignition was assumed to be controlled by chemical kinetics. The resulting equation for dimensionless ignition temperature is given below:

$$\frac{1}{\Theta_{\infty,I}} = \left[\frac{1}{(2E_w^{+}+1)}\right] \ln (D_{c,g}) \qquad [11]$$

where

$D_{c,g}$ = Damköhler group for the gas ignition temperature
E_w^{+} = dimensionless activation energy for a surface reaction
$\Theta_{\infty,I}$ = dimensionless ignition temperature at infinity

The heterogeneous ignition temperature proposed by Annamalai and Durbetaki (1977) assumes no gas phase reactions nor pyrolysis, a negligible radiant heat transfer, low mass transfer rates, and a high oxygen concentration. An energy balance about the particle with Semenov's ignition concept is used to develop an expression for ignition temperature of a particle as follows:

$$\frac{1}{\bar{\Theta}_{\infty,I}} = \left[\frac{1}{(1-\bar{a})}\right] \ln (D_{c,h}) \qquad [12]$$

where

$D_{c,h}$ = Damköhler number for heterogeneous ignition temperature
$\bar{\Theta}_{\infty,I}$ = dimensionless ignition temperature at infinity
$\bar{a}$ = constant

The theories concerning ignition temperatures derived above have assumed a steady state and a uniform dust cloud in which the walls of the chamber holding the cloud have no effect. The experimental devices used for measuring the ignition temperature of a dust cloud produce clouds with nonuniform dust concentration and nonuniform dust particle-size distribution. The point of cloud ignition is likely to be the chamber surface. Analysis should be performed that more closely models experimental ignition of a dust cloud.

Minimum Explosible Concentration

Jaeckel (1922) and Tanaka (1977) modeled the minimum explosible concentration for standing coal dust clouds. Smoot and others (1976) modeled the minimum dust concentration required for sustained propagation of a standing, laminar, coal, dust-air flame.

Jaeckel (1922) balanced the energy required to elevate the dust cloud to the ignition temperature and the concentration of dust required

to liberate this amount of energy. The result is given as

$$C_d = \frac{(T_i - T_o)\rho_a C_{v,a}}{\{q - (T_i - T_o)C_{v,d}\}} + \frac{q_l}{\{q - (T_i - T_o)C_{v,d}\}} \quad [13]$$

where

$C_{v,a}$ = specific heat of the air at constant volume
ρ_a = density of air
q = heat of combustion of dust
$C_{v,d}$ = specific heat of dust
T_o = original temperature
T_i = ignition temperature
C_d = dust concentration in the cloud
q_l = heat loss through radiation to the distant surroundings

To determine the minimum explosible dust concentration, Tanaka (1977) assumed that a flame front existed around a particle and that it was at a specified temperature. The air temperature beyond the flame front was calculated by assuming that the conductive heat transport, flame geometry, flame front size, relative distance between dust particles, and position of the stationary air molecules were constant for the time it took one particle to burn completely. To balance the heat around a second particle, the particle density, particle heat capacity, particle size, flame, and gas emissivities must be known. The time required to preheat a nonburning particle to ignition temperature by the first burning particle should equal the time required for complete combustion of the first burning particle. The distance between the first burning particle and a neighboring particle would affect the time required to preheat the nonburning particle. When the burning particle burned out just as the second particle began to combust, the distance between particles was used to calculate the minimum concentration. Tanaka (1977) assumed a uniform dust concentration.

This analysis of the minimum explosible concentration uses the ignition temperature previously calculated (eqns. [9] and [10]) and assumes a surface heterogeneous reaction. But in the analysis of the minimum explosible concentration, a flame front is assumed to exist at some distance from the surface. Such a flame front implies that a homogeneous gas phase reaction occurs. The energy needed for pyrolysis or vaporization to produce gases or vapors for a homogeneous reaction is ignored. This completely arbitrary selection of the basic combustion phenomenon is awkward.

Saskashita and others (1975) studied the lower limit of a dust explosion. The relation between a dust cloud concentration and the probability of an explosion ϕ (x) was expressed as an S-shaped curve:

$$\phi(x) = \frac{(\alpha+\beta+1)!}{\alpha!\beta!} \int_{x_1}^{x} \left(\frac{x - x_1}{x_2 - x_1}\right)^{\alpha} \left\{1 - \left(\frac{x - x_1}{x_2 - x_1}\right)\right\}^{\beta} \frac{dx}{x_2 - x_1} \quad [14]$$

where

x = concentration of dust cloud
x_1 = lower limit of dust concentration
x_2 = upper limit of dust concentration
α,β = empirical parameters

Smoot and others (1976) modeled a laminar coal dust cloud standing flame to determine the theoretical flame speed. Mass and energy balances were performed to develop the governing partial differential equations that were solved numerically. Thus, the minimum dust concentration permitting propagation of a dust cloud flame was determined.

Theoretical analysis of a minimum explosible concentration of a dust cloud has received little attention, even though results of the available analyses are far from satisfactory. The most obvious reason for lack of interest in modeling of this phenomenon is inaccuracy of the experimental measurements of this parameter. Instruments presently being developed for measuring *in situ* particle-size distribution and concentration should provide much more accurate values. In addition, including data on particle-size distribution should improve the theoretical analysis.

Flame Propagation in Dust Clouds

A comprehensive review of flame propagation mechanisms in coal dust clouds was presented by Essenhigh (1976). He employed flame propagation theory to develop a set of concepts that describe the experimentally observed flame speed of a combustible dust-air mixture. The three modes of heat transfer that describe preheating of a dust-air mixture from an ambient temperature to an ignition temperature capable of sustaining an exothermic reaction are conduction, radiation, and convective exchange.

The maximum achievable flame speed modeled by conductive or radiative heat transfer is 1.5 m/sec. Since experimental coal dust explosive flames have been recorded at 2,000 m/sec (detonation), neither of these mechanisms seem appropriate for modeling dust explosions.

Essenhigh (1976) stated that turbulent mixing is the most probable mechanism for controlling explosion wave speeds. This is an important conclusion, which has been confirmed by Bartknecht (1978b). No analysis has been attempted to describe turbulent heterogeneous explosions.

Wen and Fan (1975) examined concepts of macro- and micro-mixing in the analysis of chemical reacting flow systems. Macromixing defines the variation in residence time experienced by molecules passing through a flow system. Micromixing can be applied to turbulent particle (heterogeneous) combustion where the oxidizing gas concentration, the volatized gas concentration, and the particle-size distribution can be varied throughout the reaction zone.

Existence of a stable self-sustained detonation in a dust-air mixture has not been demonstrated. However, flame speeds and pressures ($\sim$ 25 to 30 bars), as expected in a proper detonation, have been observed indicating that at least quasi-stable detonations have occurred. Bartknecht (1978b) provided data for detonation in long tubes. Many researchers, however, feel that a deflagration to detonation transition in a dusty oxidizing atmosphere is unlikely in industry (Griffith 1978, Palmer 1973). In a premixed gaseous detonation, no restrictions are imposed on the overall reaction rate by diffusion or adsorption mechanisms that are likely to be present in a heterogeneous "detonation."

Krazinski and others (1978) and Tanaka (1977) also discussed flame propagation in dust-air mixtures. The model proposed by Krazinski and others includes radiative and conductive heat transport in a two-phase energy equation designed to compute the adiabatic flame speed. Heterogeneous carbon gasification of carbon-to-carbon dioxide is included in the model, but effects of volatiles normally present in coal are ignored. A numerical analysis was used to solve the resultant equations. The model predicts that the flame speed for 40-μm to 160-μm diameter coal particles is relatively insensitive to particle size.

Tanaka's (1977) analysis of the propagation of a dust flame is an extension of the analysis of the ignition temperature of dust particles and the minimum explosible concentration of dust clouds. The burning velocity was calculated by dividing the limiting distance between the particles by the limiting time between particle ignitions. The limiting distance and the time between the particle ignitions were determined by repeated calculation of the distance between the particles used in calculating the minimum explosible concentration until a constant distance and time was found. The burning velocity for a cornstarch dust cloud was 0.5 m/sec. The particle velocity was generated by increased gas temperature and combustion products. Total explosion-wave velocity is the sum of the burning and particle velocities. The particle velocity can be calculated if the reaction stoichiometry, the molecular weight of the solid, and the combustion gas temperature are known. Tanaka calculated the particle velocity for a starch dust cloud flame to be 40 to 50 m/sec. Because the particle velocity is two orders of magnitude greater than the burning velocity, the latter velocity can be neglected in calculating the flame speed.

Problems with earlier analyses by Tanaka (1977) regarding the minimum dust concentration are also valid for analysis of the burning velocity. Assumptions of constant geometry and conductive heat transport during flame propagation are questionable because the air surrounding the particles experiences a 40 m/sec velocity surge from development of gaseous combustion products.

The basic question in the development of a theoretical analysis of the propagation of dust explosions is whether a steady detonation can first be developed or, second, be propagated in a dust cloud. This question must be answered experimentally, but strong evidence suggests that this is possible (Bartknecht 1978b).

Pressure Development

Theoretically analyzing pressure development during an explosion in a vessel predicts the

pressure in the vessel at any position and time. If the structural strength of the vessel is known, the need to vent the vessel can be determined. This analysis should predict the effect of venting on pressure in the vessel.

Several researchers studied pressure development resulting from a gaseous explosion in an unvented vessel. Edwards and Leinbach (1935) studied the explosibility of agricultural and other dusts as indicated by the maximum pressure and rate of pressure rise. To compare the explosibility of dusts, three important factors that enter into an explosion reaction should be taken into consideration: the maximum pressure developed during an explosion, the average rate of pressure rise, and the maximum rate of pressure rise. The rate of pressure rise is responsible to a large extent for the damage. If the rate is high enough and the pressure cannot be relieved by vents, serious damage will occur. Bradley and Mitcheson (1976) reviewed several proposed models that were used to predict the time-dependent average pressure in a vessel.

Two models of pressure development resulting from a gaseous explosion in a closed vessel were presented by Bradley and Mitcheson (1976). The first model, an approximate computer solution, assumes a constant flame speed throughout the combustion process, a spherical vessel with a central ignition, an infinitely thin reaction zone, a constant pressure with respect to position in the vessel, a constant number of moles of gas, a constant ratio of specific heats, an isentropic compression of the unburned gas, and a pressure rise that is proportional to the mass fraction of the burned dust. By simulating a small change in pressure from heat released by the explosion, calculations were made of the temperature of unburned gas from the isentropic compression, mass of unburned gas, volume of burned gas, and density of burned gas, and time required to accomplish the original change in pressure, assuming flame velocity is constant.

The second model, an exact computer model, assumes flame velocity as a function of temperature and pressure, ratio of specific heats related to component concentrations, number of moles of gas based on a stoichiometric species balance, finite reaction zone thickness calculated from a conductive heat transfer mechanism, constant pressure with respect to space in the vessel, isentropic compression of the unburned gas, no heat transfer between layers of burned gas, spherical vessel with central ignition, and a quasi-equilibrium flame temperature after every mass decrement. Gas volume within the vessel is divided into three sections: burned gas, unburned gas, and gas in the reaction zone. The calculation procedure assumes that a small amount of gas is consumed in the reaction zone. Burned gas temperature, flame thickness, burning velocity, and unburned mass are calculated; and an iterative procedure determines the rise in pressure. Pressure is estimated; and isentropic temperature rise is calculated in the unburned gas, unburned gas volume, reaction zone volume, massed gas in the reaction zone, isentropic temperature rise and gas constant of each previously burned gas element, and burned gas volume. If the sum of burned, unburned, and reaction zone volumes does not equal the vessel volume, a new pressure is estimated. The process is repeated until equality in volume is achieved. When the new pressure is known, time required is calculated for the original change in mass.

In subsequent papers, Bradley and Mitcheson (1978a, 1978b) modeled venting of gaseous explosions. Equations for mass flow rate of gas from a vessel were assumed to be functions of vent area, gas density, ratio of specific heats, ambient pressure, and coefficient of discharge of the vessel vent. An exact computer analysis of pressure development in closed vessels was extended to vented explosions by numerically solving the governing equation to determine mass versus time of burned gas, unburned gas, mass of gas in the reaction zone, and mass of gas vented from the vessel through the vessel wall.

Nagy and others (1971) presented data from experiments and reviewed the literature on gas and dust explosions in closed vessels to show the effects of vessel size and shape, initial pressure, temperature, and turbulence, fuel-air ratio, and strength of ignition source on pressure and rate of pressure rise. They attempted to correlate some of these parameters with a simple mathematical model in analyzing data for 17 vessels—

spherical, cubical, cylindrical, and rectilinear—ranging from 0.018 to 905 cubic feet. The mathematical interpretation of the explosion phenomena was in general agreement with the experimental data, and correlation was obtained for several factors affecting explosion development. Neither vessel size nor shape affected maximum pressure. Rate of pressure rise decreased as vessel size increased, and the rate was proportional to the ratio of the surface area of the vessel to its volume.

Bradley and Mitcheson (1978a) deviated from the normal presentation of data, which employs the ratio of required vent area to vessel volume. A new parameter $\overline{A}/\overline{S}_o$, defined below, was used:

$$\frac{\overline{A}}{\overline{S}_o} = \frac{\left(\frac{C_d A_v}{A_s}\right)}{\left[\frac{S_o}{A_{u,o}}\left(\frac{\rho_{u,o}}{\rho_{b,o}} - 1\right)\right]} \qquad [15]$$

where

C_d = coefficient of discharge
A_v = vent area
A_s = total area available for venting
S_o = initial burning velocity
$A_{u,o}$ = initial acoustic velocity in the unburned gas
$\rho_{b,o}$ = initial gas density in the burned gas
$\rho_{u,o}$ = initial gas density in the unburned gas

Numerical values used in solving problems that employed this new parameter are unchanged for twice the flame velocity.

In a later paper, Bradley and Mitcheson (1978b) reviewed data from 34 experimental studies and 33 empirical and semi-empirical equations developed to measure and describe the development of maximum pressure in explosions. Variations between experimental data and theoretical curves were attributed to variations in the burning velocity induced by turbulence and pressure wave generation.

Few researchers have reported theoretical analyses of pressure development for dust cloud explosions: Palmer (1975) referred to several German studies in which theoretical analyses were proposed; Heinrich (1970, 1966a, 1966b, 1966c) determined the area required to vent maximum pressure developed by a dust explosion; and Palmer (1974) determined maximum pressure developed in a vented dust explosion by first calculating the amount of dust lost from the original vented vessel. The amount of dust remaining in the vessel determined the estimated rise in pressure of the vented vessel. Pasman and others (1974) determined the required vent area by equating the discharge rate from the vented vessel with the rate of product gas generation. The analysis included both flame velocity and the turbulence factor.

Theoretical analysis of pressure development in a dust explosion will most likely come after derivation of a model that accurately describes pressure development in gaseous explosions. An extension of the work of Bradley and Mitcheson (1978b) to a dust cloud would be a reasonable approach. However, gas and dust explosions differ. The flame thickness in a dust cloud is much greater than in a gas. The difference may affect the theoretical description of flame propagation and heat evolution.

If a dust cloud can be detonated, the theory of pressure development will be similar to that for a gaseous mixture. As in a gaseous mixture, detonations usually occur in vessels with length-to-diameter ratios greater than five.

Minimum Ignition Energy

Minimum ignition energy is the minimum energy required to ignite a dust cloud. The concept has been discussed by Lewis and von Elbe (1961), and numerous data have been published (Jacobson and others 1961, 1962, 1964; Nagy and others 1965; Dorsett and Nagy 1968). Line and others (1959) studied lycopodium dust clouds suspended in oxygen-nitrogen mixtures. They found that the spark ignition of lycopodium could not be characterized solely by a minimum spark ignition energy as determined in the usual manner for gases. The energy appeared to be strongly dependent on the electrical characteristics of the spark current that affected the discharge time—as the discharge time increased, the ease of ignition went through a maximum.

Eckhoff (1975) reviewed the literature on spark ignition of dust clouds. He found that the spark energy required for igniting a given dust cloud was dependent on the characteristics of the spark discharge, especially the spark discharge time. By designing a special spark gen-

erator, he was able to ignite a dust cloud explosion at a much lower energy level (1 mJ or less).

We have found no documented records of theoretical analyses of the minimum ignition energy of a dust cloud as related to any of the physical properties of the cloud or to any of the explosibility parameters, such as the minimum ignition temperature or minimum concentration. We envision derivation of a reasonable estimate of the minimum ignition energy from minimum ignition temperature, minimum explosible concentration, and an energy balance around the spark and the cloud, as long as the spark effects on the uniformity of the cloud concentration are not significant.

Dust Explosions in Grain Industries

Since the first major grain elevator explosion reported to USDA in 1898, when 10 people in Toledo, Ohio, were killed and 5 were injured, investigations of dust explosions in industries that store or process grain have been conducted periodically. Price and Brown (1922) reviewed comprehensively dust explosions up to 1922 in flour mills, elevators, feed and grain mills, starch and corn products plants, rice mills, sugar refineries, and wood-working plants. The review included location, date, probable causes, number of injuries and deaths, and monetary losses from property damage. Explosions that occurred between 1913 and 1922 were investigated personally by Price and Brown (1922). Several separate investigations also were conducted during this period (Price 1919, 1924; Raynor and Kimlel 1920; Riley 1920; Helmkamp 1919).

The most extensive investigation of dust explosions in grain industries was conducted by Gooijer and others (1975). They classified over 500 dust explosions according to cause, machine, type of industry, type of dust exploded, date and country, and recorded the number of casualties and damage. From 1860 to 1973, in over 45 percent of the cases, the causes of explosions were unknown. From 1949 to 1973, major causes of dust explosions in four industries are given in table 2. The major causes for explosions in flour and starch industries are known. From 1958 to 1975, Verkade and Chiotti (1976) did a similar review for grain elevators and feed mills. Graziano (1978) covered 1975 to 1978.

Many causes of dust explosions in grain elevators have been identified. They include:

1. matches and smoking
2. open flames such as welding and naked lights
3. small scale fires
4. electrical
5. static electricity
6. choke-ups and friction

Conditions necessary for dust explosions are

1. Proper mixture of dust and air in suspension
2. Exposure of the mixture to a sufficiently strong source of heat with dust concentration in the explosible range to initiate flame propagation through the cloud

In view of the hazard potential in a grain elevator, the Office of Safety and Health Administration, has published a Grain Elevator Hazard Alert (Bingham 1978) to assist employers in meeting their responsibilities by highlighting pertinent requirements and making recommendations regarding hazards and their abatement in the grain industry.

TABLE 2.—*Major causes of dust explosion from 1949 to 1973 (Gooijer 1975)*

Industry	Probable major causes	Causes unknown
	Percent	*Percent*
Flour mill	welding (28) hand lamp (21) electrical spark (14)	14
Feed mill	welding (25) foreign material (10) hand lamp (7)	29
Storage and transportation	welding (17) foreign material (10) friction (7)	51
Starch factories	high temperature (22) foreign material (22) static electricity (15)	6

Prevention of Grain Dust Explosions

Urgent efforts for preventing industrial plant dust explosions are being concentrated on developing methods for dust explosion control in grain elevators (Frye 1978). The scale of operation, size of the plants, large quantities of dust produced during handling, elevating, and storing grain, and availability of ignition sources make necessary a thorough investigation of dust explosions. Price (1935) listed several measures for preventing and controlling dust explosions. They include

1. explosion venting areas in grain handling and milling plants
2. removing foreign material from grain
3. noninterconnected storage bins
4. protecting electrical appliances and equipment
5. controlling static electricity
6. protecting inert gas in grinding and pulverizing operations
7. collecting and removing dust

Some of these preventive measures require minimum effort and, basically, common sense. In this review, two areas of preventing explosions will be discussed. They are methods of preventing rapid exothermic chemical reactions and methods of preventing damaging overpressures.

Methods of Preventing Rapid Exothermic Chemical Reactions

Present methods of reaction quenching involve combustion detection and quenching. An understanding is needed of the time scale and sequence of an explosion related to methods of combustion detection and reaction quenching. Progression of an explosion (table 3) is related to the reaction detection method and the reaction quenching system. If rapid exothermic oxidation of the dust can be stopped, rapid pressure increase will also be stopped. If a pressure increase can be eliminated, serious structural damage resulting from a dust explosion can be avoided.

Combustion detection methods and reaction quenching methods described in the literature are reviewed, followed by a brief consideration of possible explosion and hazard detectors that could be used in a grain elevator.

Combustion detection methods

The first step in quenching a reaction is detection. Devices include excess temperature, combustion product, and pressure-rise detectors.

Excess Temperature Detectors. Dust ignition sources include hot conveyor belts, hot idler bearings, rubbing belts, and spontaneous- or self-heating grain. Each of these sources can be automatically monitored. An automatic warning and elevator shutdown system could be triggered by a sensor at a temperature well below the lowest minimum ignition temperature for dust. Thermocouples are used to detect hot bearings and, in grain storage bins, to monitor hot spots created by mold or insect infestation. Stateham (1974) suggested using infrared pyronometers to detect below-surface fires in coal mines.

Combustion Product Detectors. Three types of fire detectors are aerosol, ionization, and smoke. Van Luik (1973) reported the use of a Wilson cloud chamber-type submicron particle detector (Environmental 1 type) to measure size and concentration of submicron particles emitted from burning wood and paper. The

TABLE 3.—*Combustion detection methods and reaction quenching systems for progression of an explosion*

Progression of an explosion	Combustion detection methods	Reaction quenching systems
Dust preheating or smoldering	Heat detectors: thermocouples I.R. surface temperature	Chemical inerting: gaseous inerting (N_2,CO_2) humidification
	Fire detectors: ionization detectors combustion detectors smoke detectors	
Dust cloud ignition	Light detectors	Chemical suppression
Rapid exothermic chemical reaction	Pressure detectors	Physical inerting: rock dust water sprays water barriers salt dust

minimum temperature for generation of aerosols from pine wood and bond writing paper are 160° and 260°C, respectively. The maximum particle concentration for pine wood is 9.5×10^5 particles per cubic centimeter, and the initial average particle size is 0.007 μm.

Chiotti and Morris (1978) reported that the main gaseous product resulting from corn kernels or corn dust heated from room temperature to 200°C is water. Oxygen consumption becomes pronounced at 190° to 200°C. The rates of weight loss for corn dust and cornstarch increase to 220°C but decrease before ignition. Other gases evolved from cornstarch and dust when heated between 110° to 203°C are CO_2, CO, and H_2. Cornstarch yields little or no hydrogen, but grain dust evolves a measurable amount.

Preliminary calculations of the flammability of gases evolved from grain dust (determined by methods outlined in **Causes and Effects of Grain Dust Explosions**—Flammability of mixtures of vapors, gases, and dust clouds) indicate that if the diluting gas is oxygen, the mixture will probably be flammable; if the diluting gas is air, the inerting effect of nitrogen in air probably will be adequate to render the mixture nonflammable. The most reliable method of determining flammability of pyrolysis gases is to measure it experimentally (Leuschke 1966).

Gibson and Chiotti (1977) used an ionization-type combustion detector and a semiconductor combustible gas detector to detect aerosols and vapors freed by low temperature heating of a grain dust layer on a hot plate. They found an ionization detector to be sensitive to the presence of thick dust layers. Presumably, aerosols generated by the hot plate were readsorbed by the dust above the layer in contact with the hot plate. The combustible gas detector is especially promising in pre-ignition heat detection.

Hertzberg and others (1977) used five types of combustion sensors: carbon monoxide monitor, light scattering smoke detector, two ionization smoke detectors, and a condensation nuclei monitor (Environmental 1 type). The condensation nuclei monitor is the most sensitive and is used to monitor numerous combustible materials. The carbon monoxide monitor is sensitive for detecting self-heating of coal but insensitive to incipient fires in wood and plastic combustibles.

Hertzberg and Litton (1975) reported success with an infrared optical fire detector for detecting methane flames. A triple band infrared system was used to detect methane flames and flames from a Bunsen burner without being triggered by a hot plate, incandescent lamp, sunlight, a Telsa coil, or a frictional spark.

Litton and Hertzberg (1977) designed an electrostatic precipitator for detecting submicron particles. The detector determined not only particle concentration but also particle-size distribution.

Pressure Rise Detectors. After a dust or a flammable gas cloud ignites, pressure in the combustion chamber will rise as the exothermic reaction generates combustion gases and heat. If combustion is characterized as a deflagration, pressure in the vessel will equalize throughout the vessel at the speed of sound, and the flame front will move at a velocity two orders of magnitude below the speed of sound. The pressure throughout the vessel will be approximately uniform; therefore, a pressure sensor can be used to detect ignition of a combustible atmosphere. At an early stage, even though the sensor is positioned far away from the point of ignition, the local initial explosion must be powerful enough to generate a pressure wave that has sufficient strength to be detected by the sensor.

Reaction quenching methods

A flame front can be quenched by gaseous inerting, chemical suppression, water inerting, or rock dust inerting.

Gaseous Inerting. A combustive atmosphere can be rendered noncombustive by adding nitrogen or carbon dioxide gas to reduce the oxygen supply below the combustion value. Nagy and others (1964) used carbon dioxide to inert dust clouds. The minimum concentration of dust required for explosion in the presence of 13 percent oxygen was 40 times greater than that required for 20 percent oxygen. The minimum ignition energy was increased by a similar amount for the above oxygen concentrations.

Palmer and Tonkin (1973) found that nitro-

gen containing less than 12 percent oxygen produced an atmosphere in which a phenol-formaldehyde resin would not combust.

Chemical Suppression. Chemical suppressants are used commercially to stop flame fronts. Some systems, described by Gillis (1977, 1978) and by Bartknecht (1971), use a pressure sensor to detect pressure buildup from ignition. The pressure sensor triggers the release of gaseous halogenated methane (halon) or other chemical suppressants. Bromine ions, or other active ions, disassociate and combine with radicals participating in the combustion chain reaction and quench the flame front. Iya and others (1976) and Avondo and others (1978) reported that the suppressing action of bromine takes place in the gaseous phase, but explosion wave speeds were explained in terms of a turbulent heterogeneous mixing mechanism. Therefore, using suppressants, which act in the gaseous phase, might not be appropriate for extinction of dust explosion.

Water Inerting. Water is an effective dust coagulant suppressant used in the coal industry. Emmerling and Seibel (1975) discussed using water sprays in controlling dust generated by continuous mining machines. Seibel (1976) evaluated the use of water and foam sprays to control dust at transfer points in coal handling systems.

Quenching a flame front can be accomplished with water sprays. Rae (1972) used various spray nozzle arrangements to halt propagation of a flame or explosion front in a large (400 m long) coal mine gallery. Spray directed toward the flame front at an angle of 45° from the floor was most effective.

Water barriers are also used to quench explosions in coal mines. Meerbach (1971) described water trays or buckets suspended on shelves at the top of a coal mine gallery. Explosion pressure waves tipped over the water trays and the explosion was quenched.

Liebman and others (1976) discussed the use of three water barriers in coal mines. The first type was a simple bucket, which was upset by the explosion dynamic pressure. The second and third types were pressure activated water dispensers. Pressure sensitive barriers were adjusted to dump their water at static overpressures as low as 0.5 psi. The barrier should be at least 75 ft from the ignition source and no further than 300 ft.

Cybulski (1973) described the effect of a wet gallery on the amount of solid inertant mixed with coal dust necessary to halt an explosion. The amount of inertant necessary for inerting a wet gallery was 50 percent of that necessary for inerting a dry gallery. Nagy and others (1964) found that for cornstarch at a concentration of 0.81 oz/ft^3, the minimum ignition energy was increased from 0.01 to 1.3 J when 0.1 oz/ft^3 of water was added to the cornstarch. Dirkzwager (1977) found that if the moisture content of cornstarch was increased 14 percent (wet basis), the minimum ignition energy necessary for ignition was approximately 20 times that for cornstarch at a moisture content of 4 percent.

Zalosh (1977) suggested water sprays for inerting at such strategic locations in grain elevators as conveyor transfer points, elevating legs, and at rail and truck dump pits. The required application rate of water was calculated to be 0.24 pound of water per pound of dust.

Rock Dust Inerting. Rock dust has been used for inerting coal dust in Belgium, Canada, Czechoslovakia, France, Germany, Holland, Ireland, Italy, Poland, South Africa, the United Kingdom, the United States, and the U.S.S.R. (Richmond 1975). Richmond found the strength of the initiation source to be an important factor in determining explosibility of materials with low volatility. Explosibility of coal dust is directly related to its volatility, and coal with less than 10 percent volatile material will probably not support an explosion when ignited with a weak ignition source. The amount of rock dust necessary for inerting depends on the coal type. Inerting grain may not be feasible but may be applied to grain dust in storage or during transportation.

Monitoring devices

Devices described in the literature are designed to detect self-heating, ignition, or existence of a flame (Stateham 1974, Van Luik, 1973, Chiotti and Morris 1978, Gibson and Chiotti 1977, Leuschke 1966, Hertzberg and others 1977, Hertzberg and Litton 1975, Litton

and Hertzberg 1977). Research is now being conducted (Schmitt 1978) to determine possible explosive atmospheres and conditions before the onset of ignition. Devices being evaluated include flammable gas monitors other than devices that measure carbon monoxide (Affens and others 1977), *in situ* particle-size distribution and concentration monitoring devices, temperature sensors, and humidity sensors.

The flammability index of a combustible gas mixture was measured experimentally by Affens and others (1977) using a hydrogen flame detector. Influence of dust on this detector has not been reported. Hopefully, adding dust might produce a similar response in measuring the flammability index, as the addition of one or more flammable gases.

Measuring dust concentration and particle-size distribution *in situ* detects explosive mixtures. Calibrating such a device is critical to its use. Leibman and others (1977) described a device that measured light extinction to monitor dust concentration. The device was calibrated by measuring light extinction through the Hartmann bomb explosion vessel at various concentrations of dispersed coal dust samples in the vessel. Accuracy of the device for measuring dust concentration without measuring the particle-size distribution is questionable because extinction is a function of mass dust concentration in the cloud and particle-size distribution. Lack of uniform dust distribution in the Hartmann bomb also has been established (Eckoff 1976a). However, Eckhoff and Fuhre (1975) developed a photo extinction system that could be adequately calibrated. The system has subsequently been used for monitoring dust concentration in a grain elevator. But apparent variations in the *in situ* particle-size distribution caused a 30 percent variation in the calibration curve for wheat dust.

Hanna and others (1966) proposed a light extinction device for determining uniformity of a dust cloud. The calibration chamber (0.274 ft^3) contained three sensors that determined concentration variations in the chamber. Tests were also run in a large gallery (6.33 ft diameter, 20 ft long) with reasonably close theoretical and experimental extinction measurements. Problems similar to those of Liebman and others (1977) were encountered with the instrument. Dust cloud concentration cannot be determined with light extinction unless particle-size distribution of the dust in the cloud is known.

Detecting an ignition source, detecting an explosion, and preventing the rapid exothermic reaction all depend on a fundamental understanding of the mechanisms of the dust cloud, or layer ignition, propagation, and reaction kinetics. All detection methods in the literature rely strongly on a specific mechanism of ignition. Consequently, each method works for a specific ignition source. Furthermore, the methods of reaction quenching rely on a specific reaction or explosion mechanism. Selecting the most reliable explosion-prevention system will probably consist of using a set of several detectors, monitors, and reaction-quenching devices. Only until a much clearer understanding of the explosion phenomena is developed will selecting the most appropriate devices be possible.

Methods of Preventing Damaging Overpressures

Two methods that prevent damaging overpressures, after ignition, are quenching the chemical reaction (see **Prevention of Grain Dust Explosions**—Methods of preventing rapid exothermic chemical reactions) and venting the pressure developed by the explosion. The following factors must be considered in designing a system that prevents damaging overpressures:

1. What dynamic and static overpressures are damaging to the structure?
2. What is the safe vent size for maximum pressure and maximum rate of pressure rise that a dust cloud will develop?
3. How do vent construction, duct work, vent material, and location alter the effectiveness of the vent?
4. What is the vent requirement of a hybrid mixture?

Damaging overpressures

The maximum static overpressure a vessel can withstand is calculated by considering the yield strength of the materials used in constructing the vessel. For a silo constructed from concrete and structural steel reinforcing, tensile strength of concrete is assumed to be zero; and

tensile strength of the expanding silo is equal to the tensile strength of circumferential structural steel reinforcing bars (eqn. [16]).

$$P = \left(\frac{\pi}{48}\right)\frac{Sd^2}{Dw} \qquad [16]$$

where

P = maximum overpressure
S = yield strength of reinforcing bars
d = diameter of reinforcing bars
D = diameter of silo
w = vertical distance between horizontal reinforcing bars

If a 20-ft diameter silo is constructed with 0.5-in diameter structural steel bars with an approximate yield strength of 30,000 psi., and assuming a 50-percent safety allowance, a safe maximum overpressure is 3 psi.

The need to provide explosion vents for grain industry equipment is increasing. Such protection must be compatible with normal design and equipment use. In many situations, this requires that the pressure rise developed in a dust explosion should not exceed 7 KN/m² (1 psi) (Gibson and Harris 1976). Two independent methods can be used to determine the area required for explosion vents: one is based on vapor data and one is based on dust data using the cubic root of volume scaling factors. The methods are in good agreement.

Donat (1971) grouped various types of dust in three wide classes according to their $\left(\frac{dp}{dt}\right)_{max}$ values, as determined in the standard Hartmann bomb. Because the vent areas for each class of the dust must be sufficiently uniform for dusts having $\left(\frac{dp}{dt}\right)_{max}$ values close to the upper limits of the respective classes, the recommended venting areas are considerably overestimated for the dusts with $\left(\frac{dp}{dt}\right)_{max}$ values in the lower end of each class. Eckhoff (1978b) extended the work of Donat by permitting venting area to be estimated on the basis of the specific value of $\left(\frac{dp}{dt}\right)_{max}$ for the actual dust under consideration. His contribution was the adoption of a risk analysis approach to vent design. Eckhoff concluded that the safe venting of bins for grain storage can, in most cases, be achieved by means of considerably smaller (one-tenth) vent areas than those suggested by Donat.

Harris and others (1977) studied the response of glass windows to explosive overpressures. A 7-mm × 0.48-m square glass window breaks at 3.3 psi, and a 7-mm × 1-m × 1-m glass window bursts at 1 psi. The effects of wired glass and shatter-resistant filmed glass were determined by measuring the velocities of flying glass fragments from an explosion.

Vent size

Palmer (1977) reviewed existing vent size guidelines and regulations. He indicated that there are three general methods of specifying the required vent size:

1. using the vent ratio
2. using half the area of the top of the bin
3. using the National Fire Protection Association explosion venting guide (1974)

However, the vent design in relation to the plant dimensions cannot, at present, be made quantitative. Results from those three methods do not differ widely.

Bartknecht (1978b) reviewed work done at Ciba-Geigy (Switzerland) on flammable gases and dust explosions. He reviewed common empirical guides to estimate the effect of change in volume on rate of pressure change in a closed vessel. The empirical relation, called the cubic law, was valid for dust explosions in vessels with length-to-diameter ratios equal to 1, vessels with volumes greater than 20 liters, and vessels with volumes less than 1000 m³.

The cubic law for relations between vessel volume and range of pressure rise for closed vessels is also valid for vented vessels. A nomograph (Bartknecht 1978b) relates vessel volume, maximum desired vessel pressure, and rate of pressure rise of the combustible dust cloud developed in an unvented vessel with the necessary relief area. The nomograph is not valid for vessels with length to diameter ratios greater than 5 because of the flame accelerating effect of the long narrow vessel, which can be explained by the effect of pressure on the ex-

plosion pressure. A change in the initial pressure in a propane explosion from 1 bar (normal atmospheric pressure) to 2 bars will approximately double the maximum pressure and the rate of pressure change. In a deflagration, pressure throughout the vessel will equalize at the speed of sound and, therefore, will increase uniformly throughout the vessel. Pressure experienced by both burned and unburned gases will be equal. Pressurizing unburned gas before ignition by the flame front moving down the tube will cause the rate of pressure rise to increase constantly. As the flame front moves down the tube, turbulence in the flame front will cause the pressure rise to increase. Speed of the flame front might continue to increase until it approaches the speed of sound in the burned mixture. If the flame front reaches the speed of sound, pressure cannot equalize within the vessel; and a strong pressure wave will form in front of the flame front. Ignition could then be caused by shock heating, resulting in detonation.

Because maximum pressure and rate of pressure rise increase rapidly in a cylinder explosion, the vent area required will increase as the length-to-diameter ratio increases. When the length-to-diameter ratio approaches 5, the entire end of a cylindrical vessel must be used for venting. Using the highly conservative vent size requirements adopted by the Federal Republic of Germany and by Switzerland has been questioned recently by Eckhoff (1979).

Vent location and construction

Vent location in a container ($L/D > 5$) allowing the smallest increase in pressure is in the wall closest to the ignition source. The effect of the remaining space in the vessel is ignored because the explosion will be vented before the remaining portion of the vessel is involved in the explosion. If the vent location is several diameters away from the ignition source, the tube effect will be experienced. Because the ignition position is not normally known, the size should take into account any possible tube accelerating effects and resulting overpressures. Realistic full-scale tests with grain dust are in great need.

Other factors to be considered in a venting system design include vent reaction speed by mechanically operated vents, vent inertia or passive venting, restriction to the venting area such as filter bags and structural steel bracing, and vent duct work. Experimental units using pressure-activated, mechanical, pressure-operated vents for long pipes at bends and junctions were studied by Bartknecht (1978b).

Vent materials for use in passive vents were studied by Nagy and others (1950), Marshall (1977), and Pineau and others (1978). Material selection was based on bursting strength of the material versus desired overpressure. Nagy tested rupture strength of various venting materials (paper, aluminum foil, and plastic film) in a 64 ft^3 cubic vessel that had a fixed venting ratio of 2.68 $ft^2/100\ ft^3$ (14-in $\times$ 20-in vent) with a 200 g/m^3 concentration of coal dust ignited by guncotton.

The effect of filter bags on venting bag filter dust collectors was studied by Bartknecht (1977). The interior volume of the vessel containing filter bags, minus volume of the bags, was used to calculate vent requirements of the vessel, as long as the venting area was not restricted by rigid bags. The explosion vent should be located as close as possible to the pressure relief area. If the explosion pressure is vented to the atmosphere, the vessel to be vented should be as close as possible to the outside wall of the building. If long ducts are used to dump excess pressure, the vent area must be increased.

Combustion of a hybrid mixture

Flammable gases and vapors present in a dust cloud (a hybrid mixture) will increase the rate of pressure rise and, therefore, the venting requirement. Bartknecht (1977, 1978b) reported that a dust containing flammable gas should be vented as though it was an explosive gas or vapor. If the dust cloud contains more than 0.2 percent (by volume) gas, it should be considered a gaseous mixture with a much greater rate of pressure increase and subsequent vent requirement.

Additional factors that affect venting requirements are ignition intensity, turbulent mixing, and multiple containers connected in series. Maximum pressure rise does not depend

strongly on the ignition energy in a closed or vented vessel. In general, influence of ignition source is negligible if dynamite is not used (Rae 1972). In a dust explosion, the thermodynamic effect of ignition energy is that of the energy source; the hydrodynamic effect is that of adding turbulence to the dust cloud. If turbulent mixing is greater than anticipated in the venting system design, the vent will be inadequate (Eckhoff 1976a, Richmond and others 1975). If several vessels are connected in series, the ignition source and dust dispersion mechanism for each secondary dust explosion is the previous dust explosion from the connecting vessel. The rate of pressure rise in the subsequent vessels will steadily increase. If this effect is not considered in the design, the vent size will be inadequate.

Similarity between a series of connected vessels and the space between buckets in a bucket elevator has not been pointed out. The space between buckets may act like separate vessels and cause a greater pressure increase than estimated when only the vessel volume is considered.

Venting of a dust explosion is at this time one of the most reliable design methods of explosion control in an existing grain elevator. In new construction, venting, together with eliminating concrete enclosed legs, conveyors, and dust work, should be considered. The results presented by Bartknecht (1978b) illustrate that some vessel shapes and sizes cannot be vented without developing excessive overpressure. Moreover, a dust cloud with a flammable gas, which is a volume percent greater than 0.2 percent, as reported by Reay (1977), must be vented as though it were a flammable gas cloud.

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Glossary of Terms and Definitions

Baghouse The term baghouse is interchangeable with the term fabric-filter devices. Cloth dust filters are usually referred to as baghouses. They consist of a steel box enclosure containing cloth tubes. The dust laden air is passed through the cloth tubes, where the dust is removed and clean air is exhausted to the outside. A cleaning mechanism continuously removes the dust from the filter tubes. Dust falls into a hopper (part of the baghouse) and is conveyed to a dust bin.

Bin roof floor A bin floor is the section of floor where the bins are filled. The top roof portion of the silos, the grain conveyor belt, and the track for the tripper are on this floor over the bins.

Boot A boot is the bottom section of a bucket elevator leg where material is introduced into the buckets. The grain enters the boot and is picked up by the leg belt buckets.

Chokes The term choke describes a situation in which excess material fills spouts, hoppers, or machinery. When flow is completely stopped, a choked condition exists.

Choking Choking is the material build-up in a spout, hopper, or machinery before full stoppage of flow. Many pieces of process equipment rely on choking flow to provide even, measureable feeding or to reduce breakage of grain and dust generation.

Coefficient of discharge Coefficient of discharge of the vessel vent is the ratio of actual quantity of flow to theoretical quantity of flow.

Combustion Combustion is a chemical reaction process in which oxygen is one of the reactants.

Combustion wave Combustion wave is a process that moves and propagates into unreacted reactants, leaving behind burned products.

Cubic law The cubic law states that the ratio of vent area required to limit the pressure rise to a specific value in two vessels is equal to the cube root of the volumes of the two vessels. It assumes that the same explosive mixture and ignition source are used in each vessel.

Deflagration wave A deflagration wave is a combustion wave whose wave or flame speed is less than the sound speed in the gaseous products of combustion. The wave front propagates by heat conduction from the flame front into unreacted material ahead of the front causing ignition and subsequent reaction.

Detonation wave A detonation wave is a combustion wave whose wave speed or detonation velocity is greater than the sound speed plus the material velocity in the gaseous products. The leading edge of a detonation wave is a shock front. Propagation of a detonation wave proceeds by shock heating the reactants with the shock front and subsequent chemical reaction.

Distribution floor Distribution floor is the elevated area between the leg head discharge and the bin floor. It includes spouts for distribution to head house bins, belts, loadout spouts, dryers, and so forth.

Explosion An explosion is a violent chemical reaction accompanied by a rapid pressure increase. An explosion can be produced by either a rapid deflagration or a detonation.

Explosible dust An explosible dust is a dust which, if suspended in the air in suitable concentration, is capable of supporting a combustion wave.

Explosion sensitivity (E.S.) Explosion sensitivity equals the ratio of the maximum explosion pressure $\times$ maximum rate of pressure rise of a sample dust over the maximum explosion pressure $\times$ maximum rate of pressure rise of Pittsburgh coal dust, that is,

$$E.S. = \frac{\left[P_{max} \cdot \left(\frac{dP}{dt}\right)_{max}\right] \text{sample dust}}{\left[P_{max} \cdot \left(\frac{dP}{dt}\right)_{max}\right] \text{Pittsburgh coal dust}}$$

Explosion suppression Explosion suppression is a process by which the energy of a dust explosion beginning to propagate is minimized by either suppressing it rapidly or by restricting its spread.

Flame front The flame front is the region in a combustion wave where unburned reactants are heated and then react to form products.

Flame speed Flame speed, or burning velocity, is the speed of a combustion wave as it moves away from the ignition source. It is a function of chemical composition of the dust and the oxidant, heat of combustion, particle size of the dust, and the turbulence of the gas in which the dust is dispersed.

Gallery Gallery, or texas house, is the long, narrow enclosure on top of the storage tanks. It houses the bin top access and covers the distribution conveyors and other handling equipment.

Godbert-Greenwald furnace (fig. 2) The Godbert-Greenwald furnace is a vertical-cylindrical furnace, consisting of a silica furnace tube 8½ in long and 1½ in internal diameter, heated electrically. The tube is mounted vertically in a metal case with asbestos insulation. The furnace is heated until the interior wall temperature is at a specific temperature (20° to 1000°C). Furnace air is heated to a temperature between that of the furnace wall and the ambient temperature. Dust is then blown into the top of the furnace with a pressurized air stream. Ignition is considered to occur when a flame fills the cylinder and flares from the bottom of the cylinder. The minimum furnace wall temperature is recorded as the minimum ignition temperature.

Grain dust Grain dust is the finely divided material that can be aspirated (removed by air) from grain during handling.

Grain dust entrainment Grain dust entrainment involves releasing grain dust from a layer of accumulated grain dust to create a dust cloud.

Grain dust evolution Grain dust evolution means releasing grain dust from a grain mass to create a dust cloud.

Grain dust generation Grain dust generation denotes producing grain dust from a grain mass.

Hammermill A hammermill is a pulverizing machine in which a high speed rotor with hammers drive the product through a screen. It is used to reduce grain size, grain particles, or other materials. Hammermills are often used after a vibratory screen to reduce lumps and other oversized particles.

Hartmann bomb (fig. 1) The Hartmann bomb was developed at the U.S. Bureau of Mines and is now in use in many laboratories in the U.S. Department of Agriculture and Western Europe. It consists of a vertical combustion tube that is about 30 cm long and about 7 cm inside diameter; it is mounted over a brass dispersion cup of the same diameter as the tube. The volume of the bomb is about 1.2 liters. The dust under test is placed in the cup and is dispersed by compressed air passing up through the tube on the cup axis. A mushroom-shaped deflector is mounted in the cup over the end of the tube to improve dust dispersion. The ignition source may be an electric spark passing between a pair of brass electrodes mounted about 12 cm above the tube bottom, a glowing electrically heated coil of resistance wire in the same position, or a suitable electrically fired match head. Work is in progress on an international basis to standardize the dust dispersion system, the ignition source, and data interpretation and presentation.

Head The term head is most commonly used to describe the very top portion of a bucket elevator (grain elevator leg), where the product discharges and where the drive is located.

Head house The term head house applies to the portion of a grain elevator that is used to house grain-handling equipment. The head house may include bucket elevators or legs, scales, grain cleaners, grain spouts to direct grain flow to bins or conveyors, grain samplers, or other ancillary equipment. At large grain elevators and terminals, the term head house refers to the vertical building encompassing the equipment.

Heat of combustion Heat of combustion is the enthalpy difference between the reactants and the combustion products, water and carbon dioxide when the reaction proceeds at constant pressure.

Heat of reaction Heat of reaction is the enthalpy difference between the reactants and products when the reaction proceeds at constant pressure.

Heterogeneous reaction Heterogeneous reaction is a reaction in which one or more reactants or products are in different phases.

Homogeneous reaction Homogeneous reaction is a reaction in which all reactants and products are in the same phase.

Ignition sensitivity (I.S.) Ignition sensitivity equals the ratio of minimum ignition temperature $\times$ minimum ignition energy $\times$ minimum explosion concentration of Pittsburgh coal dust over minimum ignition temperature $\times$ minimum ignition energy $\times$ minimum explosion concentration of sample dust, that is,

$$\text{I.S.} = \frac{[\text{T min E min C min}]\ \text{Pittsburgh coal dust}}{[\text{T min E min C min}]\ \text{sample dust}}$$

Index of explosibility (I.O.E.) Index of explosibility equals ignition sensitivity $\times$ explosion sensitivity.

K_{st} value The K_{st} value is the maximum rate of pressure rise, $\left(\frac{dp}{dt}\right)_{max}$, produced by a deflagration within a closed vessel $\times$ the cube root of the vessel volume. Experimentally, K_{st} has been found to be independent of vessel volume, if the volume is greater than about 20 liters, and provided the turbulence and dust concentration is the same in all volumes compared. K_{st} depends strongly both on dust concentration and degree of turbulence and is thus not a true constant of the dust.

Leg casing A leg casing is the enclosed area that runs vertically from the boot to the head and is used to enclose the belt and buckets.

Leg throat A leg throat is a part of the head. Material discharged at the top of the bucket elevator is discharged from the head through the leg throat.

Lower explosibility limit The lower explosibility limit may be defined as the minimum concentration of dust in a cloud necessary for sustained flame propagation.

Mallard and Le Chatelier theory The Mallard and Le Chatelier theory was developed for describing flame propagation in a gas mixture. Conduction is considered to be the mechanism of heat transfer ahead of the flame. A simple assumption is that an ignition temperature of the gas exists below which no reaction occurs and above which the reaction is self-substaining. The theory has been extended from gas mixtures to dust suspensions.

Maximum explosion pressure Maximum explosion pressure is the maximum pressure developed by a dust sample after explosion in a closed vessel.

Maximum rate of pressure rise Maximum rate of pressure rise refers to the steepest slope of the pressure-time curve $\left(\frac{dp}{dt}\right)_{max}$ (see K_{st}) obtained from explosion in a closed vessel.

Minimum explosible concentration Minimum explosible concentration is the same as lower explosible limit.

Minimum ignition energy Minimum ignition energy is the minimum electric spark energy of the ignition source that initiates an explosion in a given dust cloud.

Minimum ignition temperature Minimum ignition temperature is the lowest furnace temperature at which ignition of the injected dust cloud occurs. It is measured in a modified Godbert-Greenwald furnace apparatus (fig. 2).

Minimum oxygen concentration Minimum oxygen concentration refers to the minimum concentration of oxygen that supports a combustion wave or dust cloud.

Primary and secondary explosions Dust explosions are characterized by transmitted pressure waves through the atmosphere during the initial stages of the explosions. These waves can throw deposited dust into suspension. The initial stages of the process, during which disturbance of the deposited dust occurs, is termed the primary explosion. The subsequent explosion when the newly disturbed dust becomes involved with the flame is termed the secondary explosion.

Pyrolysis Pyrolysis is a thermally induced decomposition process that takes place anaerobically or in the presence of limited amounts of oxygen.

Quasi-equilibrium flame temperature Quasi-equilibrium flame temperature is the temperature of a flame front in which the heat released by combustion equals the heat required to elevate the reactants to the flame temperature.

Reaction zone Reaction zone is the region within the flame front, where reactants are converted to products by a chemical reaction.

Relative flammability The relative flammability of a dust cloud is defined as the percentage of inert dust that must be mixed with the explosible dust to suppress flame propagation.

Scale floor A scale floor is the area of a grain elevator where automatic or manually operated scales are installed to weigh grain.

Semenov ignition theory Semenov ignition theory assumes a uniform temperature of reactants throughout the volume of reactants. Heat is transferred according to Newton's cooling law from the surroundings to the reactants at the surface, but there is a uniform temperature within the reactants. According to this theory, the ignition temperature is that temperature at which the heat generated from reaction within the reactants equals the heat lost to the surroundings and when the derivatives of the rate of heat gain and loss with respect to temperature are equal.

Shock wave A shock wave is a pressure wave whose leading edge is a shock front. A shock front is the surface across which pressure, density, material velocity, temperature, and all other thermodynamic and hydrodynamic flow variables are discontinuous.

Smoldering Smoldering refers to the slow propagation of combustion over or through a layer or deposit of material.

Spontaneous heating Spontaneous heating of dust or grain is a process in which heat generation from a chemical reaction with the surrounding atmosphere exceeds the rate of heat loss, for example, in wet and moldy grain.

Spouts Spouts are used to gravity flow material from one point to another. They are almost always totally enclosed and form a trough that directs the material. Totally round spouting is popular in small streams up to 10,000 bushels per hour. In high volume handling applications, square or rectangular spouting is used and has a removable cover and a replaceable "wear" liner.

Static electrification Static electrification occurs when two dissimilar surfaces are charged or electrified when they come into contact and are separated. Electrons from one material move across the boundary and associate with the other, producing an excess of positive charges on the first material and negative charges on the second.

Steady detonation A steady detonation is a detonation wave for which the wave speed and pressure jump across the shock front that remains constant in time.

Stochiometric mixture A stochiometric mixture is a balanced mixture that contains just sufficient fuel to consume all the oxidants.

Streaming current Streaming current is the flow of electricity produced by the capture or loss of electrons by a flowing fluid such as liquid, gas, or solid.

Tripper A tripper is used to divert or unload grain from a horizontal conveyor belt into a bin opening. It travels on steel rails on the bin floor or within the gallery area. The conveyor belt runs through a series of pulleys that discharges the grain to be tripped in a desired direction. Modern trippers move on their own power.

Turn head A turn head is a device that distributes or routes material or grain from one spout to several bins, spouts, or machines. The term also describes a swivel device under a machine, or bin hopper, that has a spout to route material to several places.

Upper explosibility limit The upper explosibility limit is the dust concentration above which flame propagation does not occur in a closed vessel such as the Hartmann bomb.

Upper and lower garner The upper garner is a receptacle that receives grain discharged from the legs or other conveying equipment. The upper garner holds the grain before it is discharged into a scale. The weighed grain drops into the lower garner and is discharged to other points by gravity or conveying equipment. At times, no lower garner is used, and the grain is discharged directly from the scale through a spout to other distribution points.

Wilson cloud chamber A Wilson cloud chamber is a chamber in which a supersaturated condition is achieved by adiabatic expansion of a saturated vapor. Small particles initially present in the air act as nucleation sites for condensation. This chamber is used to measure aerosol particle-size distribution.

"Zeta" potential The voltage across the interface between two materials is called the zeta potential (see static electrification).

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